JOURNAL OF AGRICULTURAL RESEARCH

DEPARTMENT OF AGRICULTURE

VOL. V WASHINGTON, D. C., NOVEMBER 8, 1915 No. 6

EXPERIMENTS IN THE USE OF CURRENT METERS IN IRRIGATION CANALS

By S. T. HARDING,

Irrigation Engineer, Office of Public Roads and Rural Engineering

INTRODUCTION

Comparisons of the relative accuracy of measurements made in irrigation canals with current meters using different methods are made in the following discussion. In connection with field experiments made on the flow in various types of canals in order to determine the value of the coefficient *n* of Kutter's formula,[1] detail current-meter gagings were necessary. These detail gagings and other observations made at the same time have been used to compare the results obtained by the standard two-point, single-point, and integration methods, as well as by floats and various selected points of measurement. Much experience is now available in regard to the various methods of current-meter observations used in natural channels. The results given here apply to the more regular artificial channels used in irrigation for which there are fewer available data.

In the experiments referred to, the current-meter readings were carefully taken at from 12 to 20 points horizontally across the canal section, from four to six readings being made at each point. These detail or multiple-point observations were plotted, and the mean velocity at the different points observed was determined from the vertical velocity curves drawn through the plotted observations. The points across the canal at which observations were made are referred to in the following discussion as the "verticals." The results secured by the multiple-point reading both in each vertical and for the discharge as a whole have been taken as the correct velocities and discharges in the comparisons made. In canals of the size used in most of these experiments determinations of

[1] Ganguillet, E., and Kutter, W. R. General Formula for the Uniform Flow of Water in Rivers and Other Channels; translated from the German, with . . . additions . . . by Rudolph Hering and J. C. Trautwine. ed. 2, 240 p., pl. New York, 1893.

Journal of Agricultural Research,
Dept. of Agriculture, Washington, D. C.

Vol. V, No. 6
Nov. 8, 1915
D—1

the discharge by other methods than by the use of the current meter would not have been practicable. Greater detail regarding the methods used and the experiments in general will be found in a recent publication,[1] which discusses the results of the determinations of the value of n in Kutter's formula. The field work was carried on by various members of the Division of Irrigation Investigations, as stated in the bulletin referred to.

COMPARISONS OF DIFFERENT METHODS OF MEASUREMENT OF VELOCITIES IN THE VERTICALS

There are four principal methods by which the velocities in different verticals are determined with the current meter: The multiple-point method; the mean of the velocities at the 0.2- and 0.8-depth points, called the "two-point method"; the velocity at 0.6 depth, called the "single-point method"; and the vertical-integration method.

As the main purpose of these experiments was the determination of the value of n, it was desired to make the discharge determinations with as great accuracy as possible. The multiple-point method was used, readings being taken usually at six points in each vertical. This was assumed to give the correct discharge and is the discharge used as the basis of the following comparisons.

The multiple-point readings were usually taken at 0.1, 0.2, 0.4, 0.6, 0.8, and 0.9 of the depth. The meter was held from 30 to 60 seconds at each point. From these measurements the discharge by the two-point or the single-point method was computed and compared with the results of the multiple-point method.

When the field measurements were made, in most of the experiments gagings were also made by the vertical-integration method. Generally one or two complete round trips were made with the meter at each vertical, the vertical movement being from 3 to 16 feet per minute. Much care was used to give the meter a uniform vertical velocity so that each portion of the section would be equally represented in the integrated mean. Two complete round trips were usually made, consuming from 40 to 150 seconds, depending on the depth. The meter was generally moved more slowly in the shallower sections in order to give a sufficiently long time for the reading.

In Table I are given the general results for all experiments. These are divided in five different classes of canal sections, although there is no marked variation for the different groups. These include nearly 100 experiments for the two-point and the single-point methods on canals having discharges of from 2 to 2,600 second-feet. Only 55 experiments

[1] Scobey, F. C. The flow of water in irrigation channels. U. S. Dept. Agr. Bul. 194, 68 p., 9 fig., 20 pl. 1915. *See also* Scobey, F. C. Behavior of cup current meters under conditions not covered by standard ratings. *In* Jour. Agr. Research, v. 2, no. 2, p. 77–83. 1914.

with integration methods are shown, as measurements by this method were not taken in all cases.

TABLE I.—*Variation in discharge in percentage by the two-point, the single-point, and the integration method, compared with the multiple-point method*

Type of canal cross section.	Two-point method.			Single-point method.			Integration method.		
	Number of observations.	Mean difference from multiple-point.	Average variation of a single observation.	Number of observations.	Mean difference from multiple-point.	Average variation of a single observation, 5 per cent correction applied.	Number of observations.	Mean difference from multiple-point.	Average variation of a single observation.
Rectangular flumes....	27	+0.68	1.45	27	+4.90	2.21	17	+1.06	1.36
Concrete-lined trapezoidal sections......	15	+ .86	1.42	15	+4.21	1.94	4	+ .72	.93
Shallow earth canals, sloping sides........	13	− .38	1.08	13	+3.11	3.42	9	− .81	2.44
Shallow earth canals, steep sides..........	25	+1.05	1.74	25	+5.02	2.44	18	+ .36	2.15
Earth canals, relatively deep sections.......	16	+1.07	1.70	15	+6.32	3.18	7	+3.06	3.78
Mean of all......	96	+ .73	1.51	95	+4.80	2.54	55	+ .76	2.07

Table I shows all three methods to give an average discharge greater than the multiple-point gaging. For the two-point and integration methods this is not large, being about three-fourths of 1 per cent for both of these methods. For the single-point method the average error is +4.80 per cent. This is large enough to warrant a correction factor, so that all further comparisons with this method are based on a correction of −5 per cent made to the discharge secured by the single-point method.

Besides the average error of the series of experiments, the probable or average variation of a single observation is also given. While the mean difference of the two-point and integration from the multiple-point method is the same, the single measurements show a somewhat greater average variation for the integration than for the two-point method. If the results of the single-point observations are reduced by 5 per cent, the corrected results have an average variation but little in excess of the other methods. These results may be expressed by saying that with the two-point method a series of observations will give results three-fourths of 1 per cent too high. If no correction is made to the results, single observations will have an average error of 1.5 per cent.

The experiments covered a wide range of discharges and canal types, so that further classifications were made to determine the effect, if any, of differences in the velocity, the depth, or the value of n on the accuracy of the different methods. The results are given in Table II.

TABLE II.—*Comparisons of variations in percentage of discharge by two-point, single-point, and integration methods from discharge by multiple-point methods for different velocities, depths, and values of n*

COMPARISONS FOR DIFFERENT VELOCITIES

Observation.	Two-point method.			Single-point method (corrected by −5 per cent).			Integration method.		
	Number of experiments.	Mean difference from multiple-point.	Average variation of a single experiment.	Number of experiments.	Mean difference from multiple-point.	Average variation of a single observation.	Number of experiments.	Mean difference from multiple-point.	Average variation of a single observation.
Velocities in feet per second:									
Less than 1.00	5	+1.02	2.56	5	+1.64	3.68	3	+2.60	3.16
1.00 to 1.50	18	+ .63	1.59	18	+ .43	2.90	11	+1.62	1.75
1.50 to 2.00	12	− .38	1.60	13	+ .24	2.67	10	+1.43	2.80
2.00 to 2.50	20	+ .89	1.54	19	− .01	2.66	10	− .02	2.51
2.50 to 3.00	14	+1.67	1.68	13	− .25	1.67	10	− .18	1.41
3.00 to 4.00	15	+1.11	1.41	15	− .14	1.91	9	+ .50	1.81
Over 4.00	12	+ .02	.73	12	−2.66	2.83	2	− .43	.72
Mean	96	+ .73	1.51	95	− .20	2.54	55	+ .76	2.07

COMPARISONS FOR DIFFERENT DEPTHS

Mean depth of canal section in feet:									
Less than 1.00	14	−0.65	2.06	14	+1.02	3.66	10	+1.98	2.65
1.00 to 1.50	18	+ .21	1.23	17	+ .53	1.90	8	+1.46	1.65
1.50 to 2.00	15	+1.32	1.73	15	− .03	2.51	7	+ .86	1.49
2.00 to 2.50	22	+1.29	1.58	22	− .10	2.82	12	+1.08	2.81
2.50 to 3.00	16	+ .97	1.25	16	− .77	1.95	12	− .60	1.84
Over 3.00	11	+1.09	1.19	11	− .79	2.44	6	− .26	1.33
Mean	96	+ .73	1.51	95	− .20	2.54	55	+ .76	2.07

COMPARISONS FOR DIFFERENT VALUES OF *n*

Value of *n* in Kutter's formula:									
Less than 0.013	13	+0.40	0.76	13	−1.70	2.27	5	+0.90	0.90
0.013 to 0.017	18	+ .52	1.42	18	− .32	2.73	11	+ .23	2.25
0.017 to 0.021	20	+ .72	1.45	20	− .85	2.16	13	− .52	1.52
0.021 to 0.025	13	+ .80	2.17	13	+1.81	2.52	6	+1.87	2.91
0.025 to 0.029	11	+ .53	.88	11	− .41	2.56	5	−1.30	1.55
Over 0.029	11	+ .66	1.72	10	− .41	3.00	5	+4.35	4.35
Mean	86	+ .61	1.41	85	− .35	2.50	45	+ .59	2.14

The two-point method appears to give results equally accurate for all velocities, depths, and values of *n*, the variations which occur not being seemingly dependent on any of these three factors. The probable error of a single observation is generally less for the large velocities and

depths, which is also true of the other methods. This is to be expected, as the smaller velocities and depths usually occurred in canals of small discharge, where the general conditions for the use of the current meter are not so favorable. The accuracy does not appear to be affected by the character of the channel or value of n.

There is some indication that the correction to be used with the single-point method should be greater than 5 per cent for low velocities and less for the higher ones. This tendency is not marked, however, and it is doubtful if it is sufficient in amount or that it is sufficiently proved by these results to warrant the use of different corrections; also the correction seems to vary with the depth in a similar way.

The integration method seems to give the closest average results for velocities from 2 to 3 feet. It also appears to be more accurate for the greater depths. This latter result is to be expected. In the use of the integration method the velocity in from 0.2 to 0.3 foot in depth must be either missed entirely or imperfectly determined both at the bottom and at the water surface. The velocity at the bottom is lower than the average. Therefore the measurements in the remaining portions of the depth would give results above the actual average velocity. As the proportion of the depth for which velocities are undetermined is larger in the shallow canals, the proportionate error would be greater.

Another method sometimes used is that known as the three-point method, in which the velocity is measured at 0.2, 0.6, and 0.8 of the depth. This is more usually computed by giving the velocity at 0.6 depth equal weight with the mean of the 0.2 and 0.8 depth velocities. As Table I shows the single-point method to be less accurate than the two-point, there is no apparent advantage in the three-point method over the two-point. In sections where the two-point method gave results too low and the single-point too high, their combination might increase the accuracy over that secured by the two-point method alone. Where both were of the same sign, the use of the three-point method would give less accurate results than the two-point alone. The two-point and single-point methods gave results having opposing signs on less than one-third of the total number of experiments, so that the three-point would seem to have little advantage over the two-point method.

To definitely determine the relative accuracy of the three-point method, the discharge of each experiment was computed, using both the method by which the velocity at 0.6 depth is averaged with the mean of the velocities at the 0.2 and 0.8 depths, and also the method by which the velocities at the three points are given equal weight. This latter method would seem to be the more logical, as it has been shown that the two-point, or 0.2 and 0.8 depth method, gives results more accurate than the 0.6 point alone, so that in the use of the three points it would be preferable to reduce the weight given to the velocity at 0.6 depth.

The results of this comparison are given in Table III, which shows that the second method of computation gives the more accurate results. In no class of canal section does either three-point method give as accurate average results as the 0.2 and 0.8 depth method alone. In the individual experiments in one-seventh of the total number the $\frac{0.2+0.8+2\times 0.6}{4}$ method gave more accurate results than the 0.2 and 0.8 depth alone. In one-fifth of the total number the $\frac{0.2+0.8+0.6}{3}$ method gave results more accurate than the 0.2 and 0.8 depth alone. These were for gagings in which the errors of the 0.2 and 0.8 depth method were of different sign from those of the 0.6 method, so that their combination reduced the actual error. These cases were generally for canals of irregular section and flow, and indicate that for unfavorable conditions of current-meter work the three-point method may be preferable to the two-point, but that for usual conditions the two-point alone is preferable. However, under unfavorable conditions of irregular velocity and cross section only detail multiple-point observations can be depended upon for accurate results. The $\frac{0.2+0.8+0.6}{3}$ method is always preferable for computation of the results to the $\frac{0.2+0.8+2\times 0.6}{4}$ method.

TABLE III.—*Variation in discharge in percentage by the three-point method compared with the multiple-point method*

Type of canal cross section.	Number of observations.	Average variation from multiple-point method. Giving velocity at 0.6 depth equal weight with mean of velocities at 0.2 and 0.8 depths. Mean velocity= $\frac{0.2+0.8+2\times 0.6}{4}$	Average variation from multiple-point method. Giving velocities at 0.2, 0.6 and 0.8 depths, equal weight. Mean velocity= $\frac{0.2+0.6+0.8}{3}$
Rectangular flumes	21	+2.5	+1.8
Concrete-lined trapezoidal sections	15	+2.7	+2.0
Shallow earth canals, sloping sides	11	+1.7	+1.3
Shallow earth canals, steep sides	21	+2.5	+2.0
Earth canals, relatively deep sections	14	+3.5	+2.7
Mean of all	82	+2.6	+2.0

MEASUREMENTS WITH SURFACE FLOATS

In many experiments measurements with surface floats were made in order to secure data from which the proper coefficients for use with such measurements could be derived. It is often convenient to make such approximate measurements by timing floats over a known length of canal and applying some coefficient to the product of the velocity so

secured and the cross section of the canal in order to give the discharge. In such measurements there are two principal sources of error: (1) The cross-sectional area is difficult to obtain except in flumes or lined canals of uniform cross sections and (2) mistakes may be made in choosing a coefficient to be used in reducing the maximum surface velocities as obtained from the floats to the mean for the whole canal.

The following results relate to the proper coefficient to be used to reduce surface-float velocities to the mean velocity for the whole cross section. The average errors discussed are those arising from the determinations of float velocities and the choice of coefficients and do not include errors in determining the canal cross sections. For the other purposes of these experiments the areas of the canal sections were carefully determined. In the usual field use of float methods there may be a considerable error introduced due to errors in the approximate determinations of canal cross sections of variable dimensions, which would give larger probable errors for the discharge than would result from the probable error due to the choice of the coefficient to use with the velocity of the float alone.

Various formulas have been derived for the relation of the surface velocity to the mean velocity. These have been derived both for the relation of the surface velocity to the mean velocity in any single vertical in the section and for the relation of the maximum surface velocity to the mean velocity of the whole channel. Ganguillet and Kutter[1] give a formula, deduced by Bazin, in which the ratio of the maximum to mean velocities in a channel are made to vary with

$$\sqrt{\frac{RS}{V^2}}$$

As this term is equal to the C in Chezy's formula, a table is given for the value of the ratio for different values of C. In this formula Kutter substitutes the values of n and R from his general formula and gives a table for the values of the ratio of mean to maximum velocity, depending on R and n. The formula derived by Bazin, which forms the basis of this table, was based on 61 series of gagings.

In the canal experiments discussed in this paper in which float measurements were made several small floats would be started simultaneously at scattered points in the portion of the channel having the highest velocities. The time of the most rapid float was used to compute the maximum surface velocity. This gives lower coefficients than would be obtained by the use of the average of all floats. Small floats such as twigs or chips were used which would have both a small submergence and a small exposed surface above the water. It was found that there was little difference in the velocities of the floats thrown into the main threads of the canals unless some became caught in noticeable side

[1] Ganguillet, E., and Kutter, W. R. Op. cit.

eddies. The floats were generally timed over the 500 to 1,000 feet of canal used in the value-of-n experiment.

The value of the coefficient for each experiment was compared with the coefficient given in Kutter's table for the same value of R and n. For all measurements the coefficients differed by an average of 0.06. The mean of all observations was 0.013 lower than Kutter's. This is not an unreasonable variation when it is remembered that at best the method is only an approximate one.

The selection of the coefficient based on the value of R and n is not, however, a convenient one for field use. The determination of the canal cross section, except for flumes and lined sections, will be approximate and the determination of the value of R even more uncertain. A variation of the coefficient with the water area would be the most convenient for field use. A field measurement involves the determination of the mean cross section of the canal and the velocity of the float. If the selection of the proper coefficient is based on the cross section and an estimated value of n no additional measurements or computations are required in order to select the proper coefficients. The experiments give evidence that the coefficient varies with the character of the wetted surface, so that some knowledge of the value of n is required.

In order to determine the value of the coefficients for different conditions, the results of each measurement were plotted with the value of the coefficient and the cross-section area as coordinates. A series of curves for the different values of n were fitted to these plotted observations and adjusted until they gave results equaling, on the average, the results of the actual field determinations. From these curves the values of the coefficients given in Table IV were secured. No attempt was made to derive an equation for the variation in the value of the coefficient, graphical methods being used throughout.

TABLE IV.—*Coefficients to be applied to velocities of floats to obtain mean velocity in canals*

Area of water cross section.	Value of n in Kutter's formula.									
	0.012	0.014	0.016	0.018	0.020	0.022	0.024	0.026	0.028	0.030
Square feet.										
2	0.85	0.80	0.76	0.73	0.70	0.67	0.65	0.63	0.61	0.60
4	.86	.81	.77	.74	.71	.68	.66	.64	.62	.61
6	.87	.82	.78	.74	.71	.68	.66	.64	.63	.62
8	.88	.83	.79	.75	.72	.69	.67	.65	.63	.62
10	.88	.83	.79	.76	.73	.70	.68	.65	.64	.63
15	.89	.84	.80	.77	.74	.71	.69	.66	.65	.64
20	.90	.85	.81	.78	.75	.72	.70	.67	.66	.65
25	.91	.86	.82	.78	.75	.73	.71	.68	.66	.65
30	.91	.86	.82	.79	.76	.73	.71	.68	.67	.65
35	.91	.86	.82	.79	.76	.73	.71	.69	.67	.66
40	.91	.86	.82	.79	.76	.73	.71	.69	.67	.66
50	.91	.86	.82	.79	.76	.73	.71	.69	.67	.66
Over 50	.91	.86	.82	.79	.76	.73	.71	.69	.67	.66

From these experiments it appears that the coefficient is constant for different values of *n* for cross-section areas over about 35 square feet. The rate of variation of the coefficient is greatest for the smaller channels. The observations for cross-sectional areas over 100 square feet were too few in number to give dependable averages for canals of larger size, but both these results and Bazin's formula indicate that the coefficient is practically constant for such larger cross sections.

Similar curves were also obtained based on the value of the coefficient and the discharges. These were similar in form and indicate that the velocity within the limits of the experiments did not materially affect the ratio of maximum surface to mean velocity. These values are not given, as the coefficients based on canal areas are more convenient to use.

The results were further classified by the shape of the channel. Apparently the coefficient does not vary with the form of cross section, as the coefficient from the curves agrees fairly well with the observations when the proper values of *n* are used, whether the canal is rectangular or irregular or whether the section is deep or shallow relative to its width.

The average variation of the observed coefficients from the curves was 0.045. The average of all observations agreed with the curves, the plus variations equaling those of minus sign. Expressed as a percentage, the average variation was 6. For any single observation the observed value of the velocity coefficient is as likely to differ from the mean curve by less than 0.045 as it is to differ by more than this amount. For the average values of the coefficient this amounts to a variation of 6 per cent. In 17 of the 92 experiments, or 18.5 per cent of the total number, the observed value differed by over 10 per cent from the curves.

The more usual practice where such methods of measurements of velocities by floats are made is to use some general value of the coefficient, usually 0.80 or 0.85. These experiments, as well as the observations given by Kutter, clearly indicate that the coefficient varies quite materially for different-sized canals and for different values of *n*. These results give values for the coefficients which are less than 0.80 for all values of *n* over 0.016, becoming as low as 0.60 for small canals having high values of *n*.

The value of *n* for any given canal is, of course, uncertain to some extent. The coefficient varies most rapidly with the lower values of *n*. An error of 0.002 in selecting the value of *n* makes a difference of 5 per cent in the value of the correct coefficient to be used for low values of *n*, and less than 2 per cent for the higher values.

The coefficients to be used should be selected from the cross-section area and the value of *n*. The character of the canals corresponding to the different values of *n* given in Table IV can be secured from the general list following:

Values of n

0.012. Straight wood flume in good condition; clean concrete lining having very smooth finish; no moss or gravel.

0.014. Ordinary straight wood flumes, little rock or sand; unplastered concrete lining; no moss or gravel.

0.016. Worn wood flumes containing growths or sand and gravel; average concrete linings, irregular finish, moss growths or gravels; best earth canals, uniform silted and clean sections.

0.018. Very poor wood flumes; rough concrete with covering of moss or gravel; very good earth canals; uniform section, silted, free from gravel and moss.

0.020. Concrete in poor condition, much moss and gravel; better than average earth sections without growths and fairly regular sections.

0.022. Earth sections, generally free from moss or gravel.

0.024. Average earth canals, fairly clean and regular, some gravel and vegetation.

0.026. Earth canal; gravel and some cobbles, some moss, irregularities in cross section; masonry-lined canals.

0.028. Canals with some cobbles; moss and other unfavorable conditions.

0.030. Earth canals, much moss or weeds, irregular section, gravel or cobbles; fairly smooth rock cuts.

It is preferable to make float measurements on straight portions of canals. If it is necessary to use a length containing curves, a coefficient should be selected for a value of n about 0.002 higher than would otherwise be used.

These experiments give data both on the most probable coefficients to be used in float measurements and also on the limitations of accuracy to be expected. Such measurements are often desirable for quick approximate determinations. The most rapid of several floats should be used and the proper coefficient selected to fit the conditions. The error from the float determinations should not often exceed 10 per cent, although error in estimating the cross-sectional area may result in much larger errors in the resulting discharge for earth canals. In flumes or section of regular forms the error in determining the water area should not be large.

EFFECT ON ACCURACY OF CURRENT-METER GAGINGS FROM THE USE OF DIFFERENT NUMBERS OF OBSERVATIONS ACROSS THE WIDTH OF CANALS

The number of verticals across a gaging station at which velocity measurements should be made is a question on which there has been much difference of opinion.

In the sections of irrigation canals at which current-meter gagings are generally made, the cross section is more regular than in the usual stream gaging station, so that usually fewer measurements should be required. In the experiments discussed, measurements were made in from 13 to 20 verticals with a minimum distance apart of the verticals of 0.5 foot on the smaller canals. These measurements are more than are usual in general field practice. The results obtained were compared with the

discharge which would have been obtained had a less number of verticals been measured. The different types of canal sections were grouped into general classes. For each gaging, discharges using only every other vertical measured were computed and also using only every fourth vertical. Two computations of each gaging using the two sets of alternate verticals were made, and also two sets for every fourth vertical. These results were then compared with the discharge obtained by the use of all the verticals measured, in order to determine the probable errors to be expected when fewer verticals were used. The average number of verticals observed in the experiments was 16; the number in the comparisons averages 8 and 4. In general field current-meter work, if only 8 or 4 verticals had been measured, the ones used might have been located in the cross section differently from the arbitrary method used in this computation, so that the selection of alternate verticals as used should give errors larger rather than smaller than are to be expected. The results of this comparison are given in Table V.

TABLE V.—*Effect on the accuracy of current-meter gagings of varying numbers of verticals*

Type of canal.	Number of detail gagings made.	Average number of verticals in detail gagings.	Comparisons using one-half of observed verticals. Variation (per cent).		Comparisons using one-fourth of observed verticals. Variation (per cent).	
			Average.	Minimum and maximum.	Average.	Minimum and maximum.
Flumes, vertical sides	23	15	0.9	+0.05 to −3.82	2.9	0 to −7.50
Concrete-lined canals; steeply sloping sides	11	14	.9	−.04 to −2.95	2.9	−1.08 to −5.85
Concrete-lined canals; wide and flatly sloping sides	6	17	1.4	−.37 to −3.22	3.8	−.70 to −6.52
Average earth canals, sloping sides	18	16	2.9	+.1 to −8.3	9.2	−1.5 to −17.6
Average earth canals, steep sides	21	16	2.5	+.1 to −7.3	9.0	−.4 to −21.1
Earth canals, relatively deep sections	10	16	2.7	−.5 to −5.5	7.7	−.6 to −19.4
Mean of all	89	16	1.9	....	6.2	....

Table V gives both the average difference in percentage and the range of variations in single gagings. Occasionally the use of a less number of verticals may give a greater discharge than that obtained from a more detailed gaging, owing to irregularities in the cross section or velocity. Where an average of 4 verticals were used, less than 2 per cent of the observations gave larger discharges than the use of all verticals, so that the average difference is practically equal to the mean error. Where 8 verticals were used for all observations, one in each seven measurements

gave results larger than the use of all verticals. Except for flumes with vertical sides, however, only 7 per cent of the results were larger. In vertical-sided flumes one-third of the results were larger, so that while all experiments on flumes gave an average variation of 0.9 per cent, the mean of all variations was −0.6 per cent.

Table V indicates that in flumes or lined sections such as are usually used for canal-rating sections, the observation of velocities in from 12 to 20 verticals will give an increased accuracy of about 1 per cent over the results obtained with from 6 to 10 verticals, and about 3 per cent greater than with from 3 to 5 verticals. Under the most favorable conditions where the rating curve will remain fixed, the measurement of from 12 to 20 verticals, depending on the size of the section, may be warranted. Where the rating may be affected by channel changes during the season or under such conditions as are usually obtainable in the field, measurements based on from 6 to 10 verticals should represent good practice. The use of from 3 to 5 verticals will give results as closely as the rating curves derived can be applied to changing channel conditions in many cases and may be sufficiently close for some purposes. Using 8 verticals, only one-seventh of the results differed by more than 2 per cent; and using 4 verticals, only one-sixth differed by more than 5 per cent.

In the more irregular earth sections larger variations were found. This is to be expected, as in these the velocity and depths both change more rapidly near the sides than in the case of flumes. The use of an average of 8 verticals in earth sections gives results of similar accuracy to those obtained with only one-half as many verticals in flumes and lined sections. The use of an average of only 4 verticals gives results with average differences of nearly 9 per cent, and the variations of single experiments are much greater. It would appear that to obtain equal accuracy in gagings in earth sections with those secured in flumes about twice as many verticals should be observed. The number used will depend on the accuracy desired and the size of the canal. Less than from 6 to 8 verticals can not be recommended, and probably 8 to 12 would represent good practice. For more accurate work from 15 to 20 may be used, although where great accuracy is desired the measurements should be made in regular rating sections. Using 8 verticals, only one-tenth of the experiments differed by more than 5 per cent; using 4 verticals, one-third of the results differed by over 10 per cent.

A comparison of these results with those given for the different methods of observation of the velocity in the verticals can be made to determine the relative advantages of using either more verticals or taking more points in each vertical. The use of the 0.2- and 0.8-point method gave results averaging 0.7 per cent too high. The use of an average of 8 verticals in flumes and lined sections gave an average of 0.6 per cent too small. The use of 8 verticals obtained with the 0.2 and 0.8 method would tend to balance these errors, and in many cases might give as

accurate results as the more detailed observations. The use of the 0.6-point method gave results averaging 4.8 per cent too high, and the use of from 3 to 5 verticals in flumes and lined sections gives an average of 3 per cent too small. Apparently where few verticals are to be observed, the use of the 0.6-point method may be preferable, as the errors will tend to balance. This may be expressed by saying that about the same relative detail should be used in measuring the velocities in the verticals that is used in the number of verticals observed.

The results are obtained by using the verticals taken in the detailed measurements and selecting every alternate or every fourth vertical and computing the discharge that would have been obtained had only these verticals been observed. It is possible that gagings where the lower numbers of verticals were to be observed could be made to give closer results by using some means for the selection of the location in the canal section at which the verticals should be taken. It has been previously shown that the use of velocity measurements at the 0.2- and 0.8-depth points will give very nearly the same results as measurements at 6 or more points in the vertical and that a single observation at 0.6 gives results within 5 per cent of being correct.

If one or two points can be found in the vertical velocity curves the velocities of which can be used to determine the average velocity of the whole vertical, it would seem probable that perhaps 2 verticals on the horizontal velocity curve could be found which could be used to give the average velocity in the whole cross section. Such points, or index verticals, as they may be called, would be useful in the rougher measurements often needed in canal operation, and information as to the relative accuracy of such methods should be of value.

Two such selected verticals may be used to determine the discharge in two ways. In one the velocities only might be used and the cross-section area more carefully determined, if not known from previous observation. In the other the observed verticals may be used to obtain not only the mean velocity but also the depths at these verticals, and the width of the section may be used to determine the cross-sectional area.

The use of such index-vertical methods is, of course, most applicable to canal sections such as flumes which have practically uniform depths, as the error in determining the cross section is largely eliminated.

The measurements were examined to see whether such index verticals could be found. The horizontal velocities and cross sections were plotted on a sufficiently large scale so that the velocity and depth at any point could be read from the curves. Such index verticals would be most easily used if their distance from the sides is some definite proportion of the water-surface width. Verticals located at different points were tried. The different types of canal cross sections are discussed separately. The general results are given in Table VI.

TABLE VI.—*Discharge and velocity of various types of canals by measurements of two selected verticals*

Observations.	Number of observations.	Difference from correct discharge (per cent). Average error of all observations.	Average variation of a single observation.	Extent of variations. Plus.	Minus.
Total discharge in flumes with vertical sides:					
For points one-fifth from sides	22	+ 1.7	2.1	+ 4.5	− 1.4
For points one-sixth from sides		− 1.4	2.6	+ 5.1	− 6.5
Velocities only:					
Concrete-lined canal, steep side slopes—					
For points one-fifth from sides	10	− 2.3	2.7	+ 2.0	− 5.7
For points one-fourth from sides		+ 1.3	3.1	+ 6.1	− 3.7
Concrete-lined canals, wide and flatly sloping sides—					
For points one-fifth from sides	6	− 1.0	1.9	+ 1.6	− 5.3
For points one-fourth from sides		+ 1.4	1.8	+ 3.6	− 1.2
Average earth canals, sloping sides—					
For points one-fifth from sides	15	− 2.3	5.8	+ 9.0	−13.6
For points one-fourth from sides		+ 4.3	5.2	+15.4	− 3.8
Average earth canals, steep sides—					
For points one-fifth from sides	20	− 4.2	5.6	+ 7.2	−17.8
For points one-fourth from sides		+ 4.9	5.7	+12.1	− 6.7
Earth canals, relatively deep sections—					
For points one-fifth from sides	8	− 5.7	8.2	+10.0	−19.6
For points one-fourth from sides		+ 2.6	5.3	− 9.4	+13.8
Total discharges, points one-fifth from sides:					
Average earth canals, sloping sides	15	+ 1.1	5.0	+14.6	− 8.2
Average earth canals, steep sides	20	+ 3.3	6.0	+14.2	−10.4
Earth canals, relatively deep	8	+ 2.0	7.0	+14.1	−12.1

For vertical-sided flumes 22 gagings were available. The depths varied from 0.7 to 4.4 feet, the widths from 2 to 17.7 feet, and the discharges from 2 to 400 second-feet. The velocities and depths at points at a distance of one-fifth and one-sixth of the width from the sides were used to obtain discharges which were then compared with those obtained by the complete gaging. In such flumes with vertical sides the depths are practically uniform, and the use of the depth at only two points would cause little error in the resulting area. These results show that the two points whose mean velocities will equal that of the whole cross section lie generally between one-sixth and one-fifth of the width from the sides and that the error in using such index velocities at either proportion of the width averages about 2 per cent and does not exceed 5 per cent, except in a few cases.

For concrete-lined canals the canal section is uniform, and the cross-sectional area would be known for any depth. In such canals the discharge can be obtained from determinations of velocity and known areas for given depths. The comparisons given in Table VI are based on

velocity alone. The lined sections were subdivided into two classes: Those with relatively steep sides and those following the flatter slopes more usual to earth canals. There is no marked difference in the results of the two types. These measurements indicate, as was to be expected, that the points of mean velocity are farther from the water edges in sections with sloping sides than in the vertical-sided flumes and occur between one-fifth and one-fourth of the width of the water surface from the edges. The average and maximum errors are not large.

For earth canals results are given for both velocities and for total discharges. The results for such sections are more variable. The velocity at from one-fifth to one-fourth of the width from the edges will average to give results close to the actual velocity for the whole section, but individual gagings may vary from the mean by over 15 per cent. The results for the total discharge are more consistent than those for velocity alone. The error in the cross-sectional area, due to using the two measurements of depth to give the mean depths, tends to balance some of the errors in velocity. For all measurements the determination of the depth and velocity at points one-fifth of the width of the water surface from the sides gives average results from 1 to 3 per cent too high. Any single gaging will average to give errors of 5 to 7, and they may be as high as 15 per cent.

These results indicate that under favorable conditions two index verticals can be found in canals, the velocity at which will agree with the average for the whole cross section. These points are from one-fifth to one-sixth of the width of the canal from the sides in sections with vertical sides and from one-fourth to one-fifth for other types. In sections with vertical sides, such as flumes, and in earth sections the depths at these index verticals will also be quite close to the average depth in the whole section, so that the index points can be used also to determine the total discharge. In definite sections with sloping sides, such as concrete-lined canals, it is preferable to use known relations of depth and area and use the index points for the determination of velocities only.

Such short-cut methods would not generally be desirable at permanent rating stations. They might be useful for approximate measurements where time was an important factor, or as checks on the division of water in canal at large turnouts. Such gagings could be made of the canal above and below, and also of the turnout. Where other means of measuring or controlling the device are not available, such rapid methods might be of value.

SUMMARY

Comparisons of various methods of current-meter gaging of irrigation canals are made with measurements in which the velocities at from 70 to 120 points were taken. Canals of various types of cross section having discharges of from 2 to 2,600 second-feet and velocities of from 0.5 to 8.0 feet per second were included.

In 96 measurements the 0.2- and 0.8-depth, or two-point, method gave results averaging 0.73 per cent too high, and the 0.6-depth, or single-point, method gave results 4.80 per cent too high. The average variation for a single measurement was 1.5 per cent for the two-point method. If the results for the single-point method are corrected by −5 per cent, the average variation of a single observation is 2.5 per cent.

In 55 measurements the vertical integration method gave results averaging 0.76 per cent too high, and an average variation for a single observation of 2.07 per cent. The use of three-point methods gave errors greater than the two-point method alone.

There were no marked variations of the accuracy of any of these three methods due to difference in velocity, depth, or value of *n* in Kutter's formula.

In 92 measurements to determine the coefficient to be used to reduce the maximum surface velocity as measured by small floats to the mean for the entire cross section, the coefficient was found to vary with the value of *n* in Kutter's formula and the size of the canal. For water cross sections of over about 35 square feet the coefficient remains constant for any given value of *n*. A table is given for the coefficients for the range of conditions covered by the measurements. The coefficient varies from 0.60 to 0.91 for different conditions. The average variation of the coefficient for a single observation from the mean values was about 6 per cent, and in one-fifth of the observations exceeded 10 per cent.

In 89 experiments on the use of observations of varying numbers of verticals across the width of canals, it appears that in uniform cross sections, such as flumes or lined canals, observations in 8 verticals give an average within 1 per cent and in 4 verticals within 3 per cent of the discharge obtained with 16 verticals. In earth canals observations in 8 verticals give an average within 3 per cent and 4 verticals within about 9 per cent. For equivalent accuracy about twice as many verticals should be observed in ordinary earth sections as in uniform lined sections.

It was found that the use of only 2 verticals located from one-fifth to one-sixth of the width of the water surface from the sides of the section in canals with vertical sides such as flumes, gave results within an average of 2.5 per cent. In concrete-lined sections with sloping sides similar results were obtained where the velocities were measured at from one-fifth to one-fourth of the width from the sides, and the areas were secured from the known cross sections.

In earth canals 2 points from one-fifth to one-fourth of the width of the water surface from the sides give velocities varying from the mean of the whole cross section by about 6 per cent. Where the depths at these two points are used to give the average depth, the total discharge is determined with an average error of about 6 per cent. Errors in individual experiments were much higher.

RELATION OF SULPHUR COMPOUNDS TO PLANT NUTRITION

By E. B. HART, *Chemist*, and W. E. TOTTINGHAM, *Assistant Chemist, Department of Agricultural Chemistry, University of Wisconsin*

INTRODUCTION

The four elements, nitrogen, phosphorus, potassium, and calcium, still play the most important rôle in soil treatment. For a number of years, however, other materials which stimulate growth in vegetation have been studied by chemists and agronomists.

The so-called catalytic fertilizers, such as the salts of manganese, have often been shown to increase plant growth. In addition, studies have been made of radium, lithium, sodium, arsenic, barium, copper, and some other elements. While these may stimulate plant growth, their application is not at present regarded as of economic importance. These elements are either not at all necessary for the plant's cycle of growth or, so far as we know, are abundantly supplied in all ordinary soils.

In the case of sulphur the relation appears to be somewhat different. It was pointed out in 1911 by Hart and Peterson (5)[1] that the total sulphur content of the soils examined was low, being approximately equal to the phosphorus content. This work has been confirmed by Shedd (12) for Kentucky soils and by Robinson (11) for the important soil types of the United States. It was further shown by Hart and Peterson (5) that the sulphur content of our common farm crops was considerable, cereal grains containing about half as much sulphur as phosphorus and legume hays sometimes more sulphur than phosphorus, while the Cruciferae, such as cabbage, turnips, etc., may contain two to three times as much sulphur as phosphorus.

It has been urged by Hopkins (6) that the high sulphur content of plants does not represent their needs, but merely shows the superabundance of sulphates in the soil water, with an extraordinary consumption by the plant. This may apply to the stem and roots of plants, but not to the seed. The seeds maintain a fairly constant composition and, as shown by Peterson (9), either contain but traces of sulphates, or more probably none at all. The criticism, then, that a high sulphur content of a plant merely represents a large soil supply can not possibly hold for seeds. It is true that the sulphate sulphur and probably other forms of sulphur in the stems and roots of plants will vary with the soil supply. In these plant parts sulphates may be present where the soil supply is plentiful. The same statement, however, is equally true of phosphates.

[1] Reference is made by number to "Literature cited," p. 249.

Journal of Agricultural Research,
Dept. of Agriculture, Washington, D. C.
aq

Vol. V, No. 6
Nov. 8, 1915
Wis.—1

Minimum requirements for maximum plant development have never been established for any of the essential elements. In addition, the demands for sulphur will be related to the character of the plant compounds elaborated by the different species of plants, even in the leafy portion. A cabbage crop that absorbs 100 pounds per acre of sulphur trioxid makes use of this material in a different way from a potato crop which absorbs but 11 pounds of sulphur trioxid. In the cabbage, sulphur compounds characteristic of the species are formed in abundance, thus creating a demand for a large sulphur supply. Alfalfa hay, constructed abundantly of protein compounds even in the stem and leaf, will demand and contain more sulphur than the low-nitrogen-containing residual straws of cereals. In either of the above cases used for illustration—namely, cabbage and alfalfa—it has been found that 30 to 50 per cent of the total sulphur may be present as sulphate sulphur. Nevertheless, this makes the total organic sulphur in an acre's growth of these crops very considerable—about 30 and 50 pounds of sulphur trioxid, respectively. In this connection let us again mention the fact that the annual rainfall will carry to an acre not more than 17 to 20 pounds of sulphur trioxid, while the loss by drainage may equal and even exceed this quantity. While we have no knowledge as to whether the excess of sulphates absorbed by the plant is of physiological importance, it is, nevertheless, clear that a supply of sulphur in this form in the plant indicates that the plant has not been limited in the elaboration of organic compounds for which sulphur is necessary. In fact, we suggest that information as to whether sulphur is a limiting factor for plant growth in any soil may probably be obtained by testing for the presence of sulphates in the plants grown on that soil. Their presence would indicate that there was a sufficient supply for all constructive purposes in which sulphur is involved.

From the facts presented on crop demand and soil supply we seem perfectly justified in including sulphur with nitrogen and phosphorus in the first group of essential elements which are limited in quantity in our common soils and in constant and relatively large demand by crops. On the same basis, potassium, calcium, and magnesium fall into a second group, while iron, constituting the third group, represents an element usually in abundance in soils and utilized in but small quantities by farm crops. Consequently, on the basis of total analysis and mathematics, sulphur should be of equal importance with phosphorus. Here, however, is where very probably total analysis and mathematics will not find complete justification for their use as the sole instruments in measuring permanent soil production. In collaboration with Prof. Fred (3), the senior author has pointed out the very great difference in the effect of phosphates and sulphates on important biochemical processes in the soil. In these studies it has been shown that soluble phosphates increase enormously the number of soil organ-

isms and the rate of ammonification and destruction of organic matter, while the sulphates activate but slightly in these directions. The processes mentioned are admitted to be of great importance to the plant's nutrition and environment, involving, as they must, not only a more rapid formation of readily soluble compounds of nitrogen and a possible destruction of harmful organic materials, but a greater saturation of the soil moisture with carbon dioxid, resulting in increased solution of mineral materials necessary for rapid growth.

While from the application of analytical chemistry and mathematics we should be led to give equal importance to phosphorus and sulphur in plant production, from their relation to important soil biochemical processes we must certainly ascribe to phosphorus the more important rôle. It has been demonstrated beyond question in certain phases of fermentology that cellular and enzymic activities are markedly increased by the presence of soluble phosphates. Harden and Young (4) have shown that the activation of the yeast cell or its zymase is greatly accelerated by the presence of these substances, and we now know that such activation by phosphates is not confined to the yeast plant but may also extend to the soil flora.

Consequently, in the case of phosphorus we have at least two factors operating to make it important in the soils—supply and physiological action; while in the case of sulphur the more important rôle will be merely as a source of supply. This, however, may not always be its only function, as will be shown later, where in the case of red clover it appears to have rather specific effects on root development; but besides such specific effects it appears at present that sulphur as sulphate in the soil serves essentially as the source of needed sulphur. It, therefore, in our judgment becomes important to accumulate information as to which agricultural plants will be affected by an increased concentration of sulphates in the soil water.

For some time sulphur in its elemental form has been used in the control of certain plant diseases. Incidental to this work there has accumulated much contradictory evidence relating to its effect on the crop yield. Opinion has been freely expressed as to how it acts in the soil, but with little definite agreement. In France especially, investigations have been active on the use of elemental sulphur with a large number of different plants. Work has been done with turnips, beans, celery, lettuce, potatoes, onions, spinach, and other crops. Various results have been obtained, but generally increased yields have been reported. Boullanger and Dugardin (1) place elemental sulphur among the catalytic fertilizers and have reported very favorable results from its use. They are of the opinion that its action is on the soil flora, in some way stimulating the breaking down of organic matter and ammonia production, although their observations show that it has quite a retarding action on nitrification. They further made the interesting observation

that in sterilized soil the addition of elemental sulphur had no effect in increasing plant growth, confirming their idea that elemental sulphur acted through some influence on the soil flora. Demolon (2) believes that sulphur not only acts by stimulating the soil flora but, in addition, acts as a source of needed sulphur after it has been oxidized in the soil. He showed conclusively that flowers of sulphur would gradually oxidize to sulphates in the soil, a statement which we have confirmed and which likewise has been shown by Lint (8) to be true. The fact that elemental sulphur is oxidized in the soil probably has direct bearing on the necessity for the use or presence of adequate quantities of lime or other basic material in a soil receiving this treatment. This may not apply to all crops, but might properly explain the results secured by Wheeler, Hartwell, and Moore (16), who showed that there was injury to cereals following the application of elemental sulphur for the prevention of potato scab, unless a considerable quantity of lime had been used in the soil. From the South Oregon Experiment Station, Reimer (10) reported large increases in the yield of alfalfa by the direct use of elemental sulphur. Whether these experiments were conducted on soils of high basicity has not been reported.

The possibility of injury to the crop by partial oxidation of the elemental sulphur to sulphite must always be kept in mind. Thalau (15) has shown that sulphites of ammonium and calcium are toxic to plants in dilute solution, but probably are not so toxic in the soil itself. The fate of the elemental sulphur introduced into a soil will ultimately be its oxidation to a sulphate, but the formation of intermediate compounds and their toxic effect may account for the contradictory results that have been recorded from its use. For example, Janicaud, Hiltner, and Gronover (7) report deleterious effects with tomatoes from the use of elemental sulphur, and some of the results of Sherbakoff (14) in the treatment of potatoes for scab are of a similar order. Consequently, the attempted introduction of elemental sulphur as a source of sulphur in plant nutrition should, in our judgment, be viewed with caution.

The basis for this statement will be amplified in the following report of experimental work. After this manuscript had been prepared, the work of Shedd (13), of the Kentucky Agricultural Experiment Station, was made public. In this work use was made of a number of sulphates and sulphids, and of elemental sulphur. Good results from the use of a number of these materials are reported. Elemental sulphur and gypsum were helpful to tobacco, and elemental sulphur was materially beneficial to turnips on the soil investigated. Clover on this soil was not helped by sulphur-containing fertilizers, with the exception of a benefit from the use of potassium sulphate. Other plants, such as mustard, cabbage, and radish, showed increased growth with sulphur-containing materials.

EXPERIMENTAL WORK

Beginning in 1911, experiments have been conducted in the greenhouse to determine the influence of sulphates and sulphur on the growth of some common farm crops. Seven different crops representing three different orders have been included in the work up to the present time. They were distributed by orders as follows: Cruciferae—radish (*Raphanus sativus*), rape (*Brassica napus*); Gramineae—oats (*Avena sativa*); barley (*Hordeum vulgare*); Leguminosae—red clover (*Trifolium pratense*), bean (*Phaseolus vulgaris*), pea (*Pisum sativum*). It should be said of plants grown in this way that they sometimes do not develop so well as under field conditions. The lessened light of winter as compared with summer, for example, retards growth, and in the early fall and late spring the day temperatures are likely to become excessive. Also, possibly owing to the protection from wind and the absence of insects, the plants rarely seed well. Despite these influences, however, our crops have grown well in most cases and in some cases have developed luxuriantly. It is true, moreover, that in all cases the effect of varying fertilizer treatments is reliable for comparison, since each crop, save the food supply, was grown under conditions as uniform as possible.

METHOD OF INVESTIGATION

The soil used in this work was the Miami silt loam which predominates on the University Hill Farm. It was obtained by removing the surface vegetation and selecting the surface soil to a depth of about 4 inches. This material was then sifted through a ¼-inch screen and thoroughly mixed. There was practically no loss in the sifting, as hardly a stone was found and the sifted product was smooth and of excellent quality.

A total analysis of the soil showed the following composition, based on the dry matter: Nitrogen (N), 0.15 per cent; phosphorus pentoxid (P_2O_5), 0.14 per cent; sulphur trioxid (SO_3), 0.04 per cent; calcium carbonate ($CaCO_3$), 0.33 per cent; humus, 1.38 per cent.

The humus was determined by the official methods of analysis of the Association of Official Chemists.[1] Fifteen kilos (33 pounds) of this soil were placed in rectangular cypress boxes 16 inches long, 14 inches wide, and 5 inches deep. Seven different fertilizer treatments were tried in duplicate boxes of the soil, as follows:

Boxes Nos.

1–2. Control (no fertilizer).

3–4. Complete fertilizer:

	Gm.
Tricalcium phosphate ($Ca_3(PO_4)_2$)	12.0
Potassium chlorid (KCl)	4.5
Sodium nitrate ($NaNO_3$)	10.0

[1] Wiley, H. W., et. al. Official and provisional methods of analysis, Association of Official Agricultural Chemists. U. S. Dept. Agr. Bur. Chem. Bul. 107 (rev.), 272 p., 13 fig. 1908.

Boxes Nos.		Gm.
5–6.	Complete fertilizer+sodium sulphate (Na_2SO_4)	12
7–8.	Complete fertilizer+calcium sulphate ($CaSO_4$)	12
9–10.	Sodium sulphate (Na_2SO_4)	12
11–12.	Calcium sulphate ($CaSO_4$)	12
13–14.	Sulphur (flowers)	5

All of these materials were mixed with the soil at the beginning of the experiments, except the sodium nitrate. This was applied in solution in three separate portions as the plants developed. Sulphur was not included in the treatment of the earlier experiments. These amounts of fertilizer are equivalent to the following applications per acre to the surface 8 inches of soil, assumed to weigh 2,000,000 pounds: Tricalcium phosphate, calcium sulphate, and sodium sulphate, 1,600 pounds each; potassium chlorid, 600 pounds; sodium nitrate, 1,330 pounds; and sulphur, 665 pounds.

While these applications may appear excessive as compared with field applications, nevertheless it should be remembered that in these experiments there was a thorough and complete mixing with the entire soil mass. In some cases the soil was limed. For this purpose 10 gm. of calcium carbonate were added to each box in the set. This was at the rate of 1,330 pounds per acre of a depth of 8 inches.

Except in the case of large seeds, such as beans and peas, the seeds were sown liberally in four rows across the boxes and thinned when well developed to 16 plants per box. The larger seeds were germinated on paraffined mosquito netting stretched over distilled water, and transplanted to the soil when well developed. The usual care was taken to support the taller crops and suppress development of fungi and insects, but the use of any sulphur-containing sprays was of course carefully avoided.

When the crops were mature, they were harvested and weighed while fresh. They were then dried quickly in steam-heated trays at about 50° C. and allowed to stand exposed to the air from two to three weeks to become air-dried, in which condition they were finally weighed.

The final comparative weights will be presented in the following tables, in which the weights given are averages obtained from duplicate boxes. In some cases, as indicated, the seed has been separated from the straw and weighed separately. Owing to the difficulty in recovering the roots from the soil, they have been neglected in most cases.

LEGUMINOSAE

BEANS (*Phaseolus vulgaris*).—The variety of beans grown was Davis White Wax. In crop A only 10 plants were grown per box. This crop followed two successive crops of clover on the same soil, the first crop of clover having been fertilized. Crop A was fertilized as usual, except that no sulphur was added to boxes 13 and 14. Crop B was not fertilized. Crop C was completely fertilized. Crop D was grown on a

different set of the same type of soil, but which had produced two crops of rape (both fertilized) and three crops of radishes, the last radish crop having been fertilized. The soils were limed for this crop. The yields of air-dried crops are given in Table I.

TABLE I.—*Average weights (in grams) of air-dried bean crops*

Treatment.	Seed.					Straw and pods.				
	Crop A.	Crop B.	Crop C.	Crop D.	Average relative yields of crops.	Crop A.	Crop B.	Crop C.	Crop D.	Average relative yields of crops.
1. Control	6.4	0.7	7.1	5.3	100	15.7	12.4	34.7	26.8	100
2. Complete fertilizer	8.0	5.7	13.8	15.9	223—	21.41	19.1	42.5	45.8	144
3. Complete fertilizer + sodium sulphate.	6.9	3.4	12.9	12.8	185	18.8	20.1	46.8	43.3	144
4. Complete fertilizer + calcium sulphate.	10.4	6.3	17.3	10.1	226—	24.4	22.3	44.3	40.8	147
5. Sodium sulphate only	7.1	5.9	13.3	6.6	169	19.2	17.1	31.7	26.0	105
6. Calcium sulphate only	6.6	6.1	11.7	4.6	149	14.8	20.2	31.8	21.5	89
7. Sulphur only	3.0	4.1	1.9	0.9	51	17.9	20.3	25.3	19.3	92

The relative yields of seed showed irregular results from the application of the sulphates. When added to the usual complete-fertilizer ration, sodium sulphate depressed growth, while calcium sulphate slightly favored it. When applied alone, both salts gave results decidedly better than the control untreated soils. In this case the soluble sodium sulphate gave better results than the comparatively insoluble calcium sulphate. It seems possible that the superior results from the sodium sulphate applied alone as compared with its effect when added to the complete-fertilizer treatment may have been due to an unfavorable excessive accumulation of soluble salts in the latter case which might not occur when it was added alone.

The relative yields of straw from this crop showed no significant effects which might be due to the added sulphates. Sulphur alone was decidedly injurious to the beans. The effect is more noticeable in the case of the grain than with the straw. This might be expected to obtain, since the plants already weakened in general vitality would probably be depressed in the power of reproduction. This was more probably due to sulphites and other toxic oxidation products of the sulphur than to the sulphur itself. It could not be due merely to the acidity of the soil produced by oxidation of the sulphur, for it occurred with crop D, which was limed.

CLOVER (*Trifolium pratense*).—The variety grown was Medium Red. Crop A was grown on fresh fertilized and limed soil. Crop B followed crop A on the same soil without fertilizer treatment, but with the addition of fresh soil in boxes 13 and 14, to which calcium carbonate and elemental sulphur were applied. Crop C was grown on completely

renewed unlimed soil with the usual complete-fertilizer treatment. Crop D was grown on soil which had borne two successive fertilized crops of rape and two successive crops of turnips (*Brassica napus*), the last crop of turnips only receiving fertilizer. This clover crop was limed and fertilized. All the crops were allowed to reach the late-blooming stage, but they failed to produce seed. The roots of crops B and C were separated as carefully as possible from the soil and weighed separately from the tops. The yields of air-dried matter are given in Table II.

TABLE II.—*Average weights (in grams) of air-dried clover crops*

Treatment.	Hay.					Roots.				
	Crop A.	Crop B.	Crop C.	Crop D.	Average relative yields of all crops.	Crop A.	Crop B.	Crop C.	Crop D.	Average relative yields of crops B and C.
1. Control	31.8	56.2	11.7	92.0	100	......	49.5	16.8	......	100
2. Complete fertilizer	45.3	71.5	48.1	95.0	136	......	48.5	37.4	......	130
3. Complete fertilizer+sodium sulphate	54.8	72.2	67.0	99.8	153	......	41.4	31.9	......	111
4. Complete fertilizer+calcium sulphate	46.0	79.2	73.7	108.2	160	......	48.8	36.4	......	129
5. Sodium sulphate only	33.0	65.9	23.6	93.9	113	......	67.7	33.1	......	151
6. Calcium sulphate only	27.8	62.5	29.0	116.4	123	......	92.9	31.9	......	188
7. Sulphur only	......	49.1	23.6	......	38	......	71.9	21.5	......	141

In the yield of hay there was no doubt about a marked stimulating effect of both sulphates upon growth. Stimulation was equally evident when they were added to the complete-fertilizer treatment and when they were applied alone. In both cases the best results were produced by the less soluble calcium sulphate. Elemental sulphur had a very depressing effect. The average yield from this treatment was but little more than one-third the yield from the control, and in crop D the clover entirely failed to grow where elemental sulphur was applied. Plate XX, figure 1, illustrates the influence of sulphates on the growth of clover.

Root development from the complete-fertilizer treatment was depressed somewhat when sodium sulphate was also applied, but was unaffected when the calcium sulphate was added. We are inclined to ascribe this difference to the depressing effect of the more concentrated soil solution where the soluble sulphate was applied. The effect of the sulphates applied alone was very striking. In Plate XXI is shown the remarkable difference of root development from the different fertilizer treatments. From our limited amount of data calcium sulphate appears to be somewhat more active than sodium sulphate in producing this effect. In any case it appears that in this soil a sulphate has specific effects on the root development of this species. This may properly explain the oftentimes beneficial effects observed in the application of land plaster

to clover. While the form of the root system developed under the two treatments may not involve a larger feeding surface in the one case as compared with the other, yet it does seem very probable that the long root system developed where sulphate concentration was larger would favor that plant in times of limited water supply. The unavoidable conclusion from the results with red clover is that the reenforcement of the limited soil supplies of sulphur compounds by sulphates of sodium and calcium was decidedly beneficial to this crop.

PEAS (*Pisum sativum*).—The variety grown was Little Gem, a dwarf variety. Strong seedlings were transplanted to the soil six days after they were placed on the germinator. The soils had already produced two crops of clover and three of beans, the first crop of clover and the first and last crops of beans having been fertilized. Both clover crops had been limed. No elemental sulphur was added to box 13 and 14 for the first crops of beans. The data of the pea crop are given in Table III.

TABLE III.—*Average weights (in grams) of the air-dried pea crop*

Treatment.	Seed.	Straw and pods.	Relative yields of seeds.	Relative yields of straw.
1. Control	0.18	4.42	100	100
2. Complete fertilizer	.21	3.99	117	90
3. Complete fertilizer+sodium sulphate	.24	4.12	133	93
4. Complete fertilizer+calcium sulphate	.97	4.54	539	103
5. Sodium sulphate only	.60	4.41	333	100
6. Calcium sulphate only	.82	3.84	456	87
7. Sulphur only	.03	2.47	17	56

This crop did not grow vigorously, and the differences of yields have, therefore, less significance than with the preceding crops. However, the increased yields of seeds where sulphates were added is surely remarkable. This is especially true for the calcium sulphate, both when added to the complete fertilizer and when added alone. Both sulphates when applied alone gave remarkable increases over the control soils. Sulphur alone was much more toxic than was the case with the crops already described. The straw shows no very great differences of yields, except where sulphur alone was applied. Here the depressing effect was somewhat less than in the case of the other leguminous crops.

Probably the negative effect of fertilizers upon the growth of straw on this crop should be attributed to the fact that the soils had been excessively cropped and fertilized. This would tend, on the one hand, to exhaust the control soil and, on the other hand, to render the fertilized soils too concentrated in soluble salts for good growth. Hence, the development was even poorer in some cases than the control. Apparently the sulphates especially favored the development of seed in this weakened crop. That such was not the case where sodium sulphate

was added to the complete fertilizer may have been due, as suggested for the previous crops, to a depressing effect of an excess of soluble salts. The favorable effects of calcium sulphate were most decided.

Summarizing the results obtained with the leguminous plants, it may be stated that sulphates added to this soil were decidedly beneficial to the growth of the crops so far investigated. With the large-seeded bean and pea the effects are practically confined to the increased seed development. With the hay crop, however, the results are favorable to the growth of the straw portion of the plant. Calcium sulphate in general is considerably superior to sodium sulphate in its fertilizing action. In the case of clover both of these compounds, when added separately, increased the root development markedly. This would tend to increase the feeding power of the plant and may largely account for the increase of hay produced by their use. Sulphur alone depresses the general development of the plant, with the apparent exception of the clover roots.

CRUCIFERAE

RADISHES (*Raphanus sativus*).—The variety grown was Earliest Scarlet Turnip. Crop A followed two crops of rape on the same soil, both of which had been fertilized. Crop A was not fertilized. Crop B followed crop A on the same soil and was not fertilized. Crop C was also grown on the same soils, but was fertilized. Fifty days from planting crop A, alternate rows of the crop were harvested from one set of boxes for photographing. These were dried and the weights recorded. The remaining plants were allowed to develop seed and the residue rejected. Plate XX, figure 2, is therefore the only available comparison covering the whole crop. The air-dried yields are given in Table IV. (See Pl. XX, fig. 3.)

TABLE IV.—*Average weights (in grams) of air-dried radish crops*

Treatment.	Crop A.		Crop B (whole plants).	Crop C (whole plants).	Average relative yields of whole plants for all crops.
	Tops.	Roots.			
1. Control	0.2	2.5	19.9	10.3	100
2. Complete fertilizer	1.5	4.7	36.5	34.9	236
3. Complete fertilizer+sodium sulphate	1.2	4.7	30.5	48.0	256
4. Complete fertilizer+calcium sulphate	1.7	7.0	28.4	47.6	257
5. Sodium sulphate only	1.5	5.0	24.3	10.9	126
6. Calcium sulphate only	1.0	4.7	21.0	11.3	115
7. Sulphur only	.8	3 7	18.2	7.1	60

The results call for special comment. They show, especially where freshly fertilized (crop C), an unmistakable stimulus to growth by sulphates. The effect is much more pronounced where the sulphates were applied alone than where the complete-fertilizer ration was used. A

point of special interest in these results is the fact that sodium sulphate gave quite as good results as calcium sulphate when added to the complete-fertilizer ration. This suggests that we were dealing here with a plant more tolerant of the concentrated soil solution than were the legumes grown. The radish was also more tolerant of elemental sulphur than were any of the legumes, although the growth in its presence was somewhat inferior to that of the control plants.

RAPE (*Brassica napus*).—The variety grown was Dwarf Essex. Crop A was grown on the usual soil, fresh and completely fertilized except for elemental sulphur. Crop B followed crop A on the same soil. The soil was refertilized and boxes with elemental-sulphur treatment were added. Crop C was grown on fresh-fertilized soil. Crop D followed crop C on the same soil and with the same fertilizer applications. The rape crops were harvested when the death of the basal leaves indicated the near approach of maturity. Data of the weights of the air-dried rape crops are given in Table V.

TABLE V.—*Average weight (in grams) of air-dried rape crops*

Treatment.	Tops.					Roots.				
	Crop A.	Crop B.	Crop C.	Crop D.	Relative weights with control = 100.	Crop A.	Crop B.	Crop C.	Crop D.	Relative weights with control = 100.
1. Control	54.0	12.7	11.6	15.3	100	8.5	2.0	2.7	......	100
2. Complete fertilizer	80.5	29.0	36.4	27.7	188	11.8	3.8	5.1	......	157
3. Complete fertilizer+sodium sulphate	90.0	30.9	45.6	40.9	222	12.3	2.6	5.3	......	154
4. Complete fertilizer+calcium sulphate	78.5	32.9	45.4	50.0	221	12.5	4.9	6.3	......	181
5. Sodium sulphate alone	59.5	13.9	15.8	14.3	111	8.5	2.3	2.8	......	104
6. Calcium sulphate alone	57.0	14.7	13.5	13.3	105	8.8	3.0	3.3	......	115
7. Sulphur alone	......	13.6	12.3	4.2	32	......	3.1	2.6	......	44

It is clearly evident that the addition of sulphates benefited this crop, but especially so where they supplemented the complete-fertilizer ration. Apparently the demands for sulphur of the higher yields of tops from the fertilized plants accentuated the benefits from the sulphates in this case (Pl. XXII, fig. 1).

The sulphates of calcium and of sodium were equally efficient for rape. In the case of the roots only the calcium sulphate gave beneficial results. Possibly the soluble sodium sulphates increased the concentration of the soil solution to such an extent as to retard the growth of the roots. It is well known that in water cultures the roots of plants are more sensitive than the tops to such changes in the nutrient medium. As in water cultures, so, too, in these soil cultures, it appears that the growth of tops and of roots does not proceed parallel.

Rape was also grown upon sand. The sand employed was obtained from the Wausau Quartz Co., Wausau, Wis. It was an angular product, designated as No. 2, which passed almost completely through a sieve of 40 meshes to the inch, but was half retained by a 60-mesh sieve. It contained small amounts of impurities, but no sulphates. Fifteen kgm. (33 pounds) of this sand were placed in the usual boxes with the following fertilizer treatments:

Boxes Nos.		Gm.
1–2.	Tricalcium phosphate ($Ca_3(PO_4)_2$)	12.0
	Potassium chlorid (KCl)	4.5
	Magnesium nitrate ($Mg(NO_3)_2$)	2.5
	Sodium nitrate ($NaNO_3$)	8.0
	Calcium carbonate ($CaCO_3$)	5.0
	Iron chlorid ($FeCl_3$)	1.0
3–4.	Like 1 and 2+calcium sulphate ($CaSO_4$)	12.0
5–6.	Like 1 and 2+sodium sulphate (Na_2SO_4)	12.0
7–8.	Like 1 and 2+sodium sulphate (Na_2SO_4)	6.0

All of the salts, except sodium nitrate, were mixed with the sand before planting, but this was applied to the growing plants in portions from time to time. At 84 days of growth, when the plants gave the usual signs of maturity, the crop was harvested. The yields of the air-dried rape crops are given in Table VI.

TABLE VI.—*Average weights (in grams) of air-dried rape crops*

Treatment.	Tops.	Roots.	Relative yields when complete fertilizer=100. Tops.	Relative yields when complete fertilizer=100. Roots.
1. Complete fertilizer	39.0	4.5	100	100
2. Complete fertilizer+calcium sulphate	43.0	10.0	110	222
3. Complete fertilizer+sodium sulphate	26.5	3.2	68	71
4. Complete fertilizer+½ sodium sulphate	31.0	3.5	80	78

In these cultures the calcium sulphate was beneficial, but the sodium sulphate depressed the yields as compared with the basal complete fertilization. The data show this effect of the sodium sulphate least where the smaller amount of salt was applied. This again seems to indicate that the depressed effect was due, in part at least, to an excessive concentration of soluble salts. If such an effect were appreciable, one would expect it to be more pronounced in the case of the sand than with soil on account of the lower absorptive power of the former, and such was the case. The calcium sulphate exerted a remarkable effect on the development of the rape roots in these cultures. An objection might possibly be raised that the beneficial effects upon root growth apparent with the soil cultures may have been due to imperfect separation of the

finer parts of the root system from the soil. Such objection would not apply to the sand cultures, which therefore gave conclusive evidence of the stimulating effect of calcium sulphate upon the root development of rape. The benefit to the tops from this salt was much less pronounced, but nevertheless definite. As in most other cases, the elemental sulphur was detrimental to the plants, presumably because of toxic action. There seems to be no doubt that the rape plant has specific need for sulphur, which should be met by including sulphates in its fertilizer treatment.

GRAMINEAE

Barley (*Hordeum vulgare*).—One crop was grown upon a set of soils which had already produced one crop of peas with fertilizer treatment and a second crop without fertilizer. The barley crop was not fertilized, as the pea crops had been light. The variety planted was New Zealand Chevalier. In Table VII are given the average air-dried weights of the yields from duplicate boxes.

Table XVII.—*Average weights (in grams) of air-dried barley crop*

Treatment.	Straw.		Grain.	
	Weight.	Relative yields when control=100.	Weight.	Relative yields when control=100.
1. Control	36.5	100	9.5	100
2. Complete fertilizer	59.0	162	10.5	111
3. Complete fertilizer+sodium sulphate	67.0	184	14.5	153
4. Complete fertilizer+calcium sulphate	62.5	171	15.0	158
5. Sodium sulphate only	43.5	119	14.0	147
6. Calcium sulphate only	38.5	106	17.0	179
7. Sulphur only	39.0	107	13.5	142

The limited data available are insufficient for the deduction of definite conclusions concerning the effects of the sulphur supply upon the growth of the barley crop. They indicate, however, that sulphur and the sulphates here applied had little influence upon the production of straw in this crop either when added to a complete-fertilizer ration or when applied alone. Conditions were decidedly different in the case of the grain. While the production of straw seems to have been limited, this amount of straw produced 40 to 80 per cent more grain in the crops receiving sulphur and sulphates alone than in the control crops. Likewise, the crops receiving sulphates in addition to a complete-fertilizer ration produced about 40 per cent more grain than those receiving only the complete ration (Pl. XXII, fig. 2).

Oats (*Avena sativa*).—This crop was grown upon a set of soils which had borne two unsatisfactory barley crops, the first of which had been fertilized. The oat crop was not fertilized. Wisconsin Wonder was

the variety planted. Unlike the barley, this grain crop showed decided differences in development upon the different rations during its growth, as shown in Plate XXII, figure 3. In Table VIII are given the average yields of the thrashed crop in the usual manner, the husks being carefully removed from the seed.

TABLE VIII.—*Average weights (in grams) of the air-dried oat crop*

Treatment.	Straw.		Grain.	
	Weight.	Relative yields when control=100.	Weight.	Relative yields when control=100.
1. Control	28.5	100	2.5	100
2. Complete fertilizer	56.0	197	5.0	200
3. Complete fertilizer+sodium sulphate	57.5	202	8.5	340
4. Complete fertilizer+calcium sulphate	54.5	191	8.5	340
5. Sodium sulphate only	19.5	68	2.5	100
6. Calcium sulphate only	19.0	67	2.5	100
7. Sulphur only	23.5	82	3.5	140

The statements previously applied to the limited amount of data on barley also apply to the oats. So far as the preceding table is concerned, however, it indicates, as in the case of barley, no appreciable effect of sulphates upon the development of straw when they supplement the usual complete-fertilizer ration. Sulphur and sulphates alone even depressed the yield of straw as compared with the control crops.

In the case of the grain, the application of sulphur and sulphates alone did not increase the yield as compared with the controls, although it increased the ratio of grain to straw. The crops receiving complete fertilizer indicate a marked stimulating effect of sulphates upon seed production in this crop. Those crops receiving sulphates in addition to a complete fertilizer produced 70 per cent more seed than those receiving complete fertilizer only.

The data from these two crops of the Gramineae family have shown a marked response of these plants to the application of sulphates by increased seed production. From these records it appears that under present common methods of fertilization these grain crops may frequently reach a maximum production of straw, but that the capacity of this yield of straw to produce seed may be greatly enhanced by the addition of calcium sulphate or sodium sulphate to the so-termed complete-fertilizer ration. In future investigations the writers plan to determine whether the indications here obtained with the Gramineae express a general and fundamental sulphur requirement of this family of plants.

The influence of the concentration of the soil sulphates on the sulphur content of plants has already received consideration (9), but it will not

be out of place to include further data on that subject. Work has been done especially on clover and rape. Data illustrating this influence are given in Table IX. The crops were air-dried.

TABLE IX.—*Influence of supply of sulphates on the sulphur and potassium content of clover and rape*

Treatment.	Clover tops.							Rape.					
	Crop B.			Crop E.				Crop B.			Crop D.		
	Sulphur.	Crop.	Quantity of sulphur removed.	Sulphur.	Crop.	Quantity of sulphur removed.	Potassium.	Sulphur.	Crop.	Quantity of sulphur removed.	Sulphur.	Crop.	Quantity of sulphur removed.
	Pr. ct.	*Gm.*	*Gm.*	*Pr. ct.*	*Gm.*	*Gm.*	*Pr. ct.*	*Pr. ct.*	*Gm.*	*Gm.*	*Pr. ct.*	*Gm.*	*Gm.*
1. Control	0.15	56	0.084	0.20	28	0.056	1.58	0.60	12	0.072	0.22	15	0.033
2. Complete fertilizer	.20	71	.142	.14	85	.119	2.42	.18	29	.054	.22	27	.059
3. Complete fertilizer + sodium sulphate	.20	72	.144	.21	99	.207	2.63	.87	31	.269	.78	41	.319
4. Complete fertilizer + calcium sulphate	.20	79	.558	.25	110	.275	2.31	.90	33	.290	.70	50	.350
5. Sodium sulphate only	.11	66	.072	.13	56	.072	1.64	1.18	14	.165	1.08	15	.162
6. Calcium sulphate only	.16	63	.100	.25	61	.152	1.36	1.18	14	.165	.90	13	.117
7. Sulphur only	.19	49	.093	.22	45	.099	1.32	1.00	13	.130	1.66	4	.066

As has been pointed out, the effect of a more concentrated soil-sulphur solution is to increase the total sulphur content of the root and the stem, but not of the seed. This influence is particularly great in the case of the leafy plant like the rape, but is not so marked in the red clover. In the rape the percentage variation of sulphur ranged from 0.20 to 1, depending upon the supply, while in the clover the range was from 0.10 to 0.20. In the case of one crop of clover there is included the total potassium content of this crop. It has been common, since the time of Boussangault, to explain the action of calcium sulphate in the soil as a liberator of potassium, and its effect as indirect. This explanation might still be used for our own results where calcium sulphate was added alone. In this case the growth of crop was so much increased over the growth in the control that the total potassium removed was considerably more than in the control. But where the complete fertilizer containing potassium chlorid is compared with the complete fertilizer plus calcium sulphate, such an explanation for the action of calcium sulphate becomes untenable. The increased growth due to the calcium sulphate in the presence of a complete fertilizer containing potassium can have no other explanation than that its action was direct rather than indirect.

SUMMARY

The data presented from these greenhouse studies with one type of soil indicate that certain plants are measurably increased in their growth by the addition of sulphates. We have emphasized in another

place the fact that sulphates have very little effect as compared with soluble phosphates on the soil flora. This difference in action will remove the sulphates from the category of effective fertilizers for all crops. Nevertheless, for certain plants and types of soil they will be beneficial if their only action is as a source of sulphur.

The plants most affected were the members of the Leguminosae and Cruciferae. It is probable that we should expect these classes of plants to be more responsive to the higher concentration of sulphates in the soil water than, for example, the Gramineae, owing to the higher protein content of the first group and the special sulphur-bearing bodies abundantly formed in the second group. In this soil, however, there was noticeable stimulation to seed production in both barley and oats, although there was little or no effect on the development of the quantities of straw.

In the case of clover the increase in air-dried matter due to calcium sulphate alone was about 23 per cent. With rape the greatest increase occurred where the calcium sulphate was superimposed upon a complete fertilizer, giving an increase of 17 per cent over the complete fertilizer. A similar order of increase was likewise observed with the radish crop, where the increase above a complete fertilization, due to the calcium sulphate addition, averaged 9 per cent.

In general, the calcium sulphate was more effective than the more soluble sodium sulphate. The special influence of sulphates on root development is pointed out. They were particularly effective with red clover and rape. In the case of red clover, which was more especially studied, the roots were much elongated where sulphates entered into the ration. This must result in a more extended feeding area for the plant and, in addition, increase its ability to withstand periods of drought.

The somewhat common observation of the benefit of land plaster to this plant can probably be closely correlated with this special effect of sulphates on root development, as well as its high protein character, which would make special demands for sulphur.

Whether recorded failures in the use of land plaster are to be correlated with wet seasons, a high sulphur content normal to the soil under observation, or the variety of plants used is a matter for future observation.

In these greenhouse experiments elemental sulphur was generally harmful. These harmful results occurred even in the presence of a generous supply of calcium carbonate. These results indicate that elemental sulphur may be toxic through its incomplete oxidation to sulphites; toxicity may also arise in the absence of sufficient basic material through the development of acidity from sulphuric acid.

Application of these results to field practice is reserved until more data on field plots are available.

LITERATURE CITED

(1) BOULLANGER, E., and DUGARDIN, M.
1912. Mécanisme de l'action fertilisante du soufre. *In* Compt. Rend. Acad. Sci. [Paris], t. 155, no. 4, p. 327-329.

(2) DEMOLON, A.
1913. Recherches sur l'action fertilisante du soufre. *In* Compt. Rend. Acad. Sci. [Paris], t. 156, no. 9, p. 725-728.

(3) FRED, E. B., and HART, E. B.
1915. The comparative effect of phosphates and sulphates on soil bacteria. Wis. Agr. Exp. Sta. Research Bul. 35, p. 35-66, 6 fig.

(4) HARDEN, Arthur, and YOUNG, W. J.
1906. The alcoholic ferment of yeast-juice. *In* Proc. Roy. Soc. [London], s. B, v. 77, p. 405-420.

(5) HART, E. B., and PETERSON, W. H.
1911. Sulphur requirements of farm crops in relation to the soil and air supply. Wis. Agr. Exp. Sta. Research Bul. 14, 21 p.

(6) HOPKINS, C. G.
1911. The sulphur supply of the soil. *In* Breeder's Gaz., v. 60, no. 2, p. 51-52.

(7) JANICAUD, W., HILTNER, and GRONOVER.
1914. Wirkt Schwefeldüngung wachstumsfördernd? *In* Gartenwelt, Jahrg. 18, No. 3, p. 29-32, illus.

(8) LINT, H. C.
1914. The influence of sulfur on soil acidity. *In* Jour. Ind. and Eng. Chem., v. 6, no. 9, p. 747-748.

(9) PETERSON, W. H.
1914. Forms of sulfur in plant materials and their variation with the soil supply. *In* Jour. Amer. Chem. Soc., v. 36, no. 6, p. 1290-1300. Bibliography, p. 1300.

(10) REIMER, F. C.
1914. Sulphur fertilizer for alfalfa. *In* Pacific Rural Press, v. 87, no. 26, p. 717.

(11) ROBINSON, W. O.
1914. The inorganic composition of some important American soils. U. S. Dept. Agr. Bul. 122, 27 p.

(12) SHEDD, O. M.
1913. The sulphur content of some typical Kentucky soils. Ky. Agr. Exp. Sta. Bul. 174, p. 269-306. References, p. 306.

(13) ———
1914. The relation of sulfur to soil fertility. Ky. Agr. Exp. Sta. Bul. 188, p. 595-630. Bibliography, p. 629-630.

(14) SHERBAKOFF, C. D.
1914. Potato scab and sulfur disinfection. N. Y. Cornell Agr. Exp. Sta. Bul. 350, p. 709-743, fig. 106. Literature cited, p. 741-743.

(15) THALAU, Walter.
1913. Die Einwirkung von im Boden befindlichen Sulfiten, von Thiosulphat und Schwefel auf das Wachstum der Pflanzen. *In* Landw. Vers. Stat., Bd. 82, Heft 3/4, p. 161-209, 2 pl.

(16) WHEELER, H. J., HARTWELL, B. L., and MOORE, N. L. C.
1899. Upon the after effect of sulfur, when applied to soils for the purpose of preventing potato-scab. *In* R. I. Agr. Exp. Sta. 12th Ann. Rpt. 1899, p. 163-167.

PLATE XX

Fig. 1.—Clover plants, showing influence of sulphates on growth. 1, Check; 2, nitrogen, phosphorus, potassium; 3, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; 4, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; 5, sodium sulphate only; 6, calcium sulphate only; 7, elemental sulphur only.

Fig. 2.—Radish plants, showing influence of sulphates on growth. 1, Check; 2, nitrogen, phosphorus, potassium; 3, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; 4, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; 5, sodium sulphate only; 6, calcium sulphate only; 7, elemental sulphur only.

Fig. 3.—Radish plants, showing influence of sulphates on growth. 1, Check; 2, nitrogen, phosphorus, potassium; 3, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; 4, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; 5, sodium sulphate only; 6, calcium sulphate only; 7, elemental sulphur only.

PLATE XX

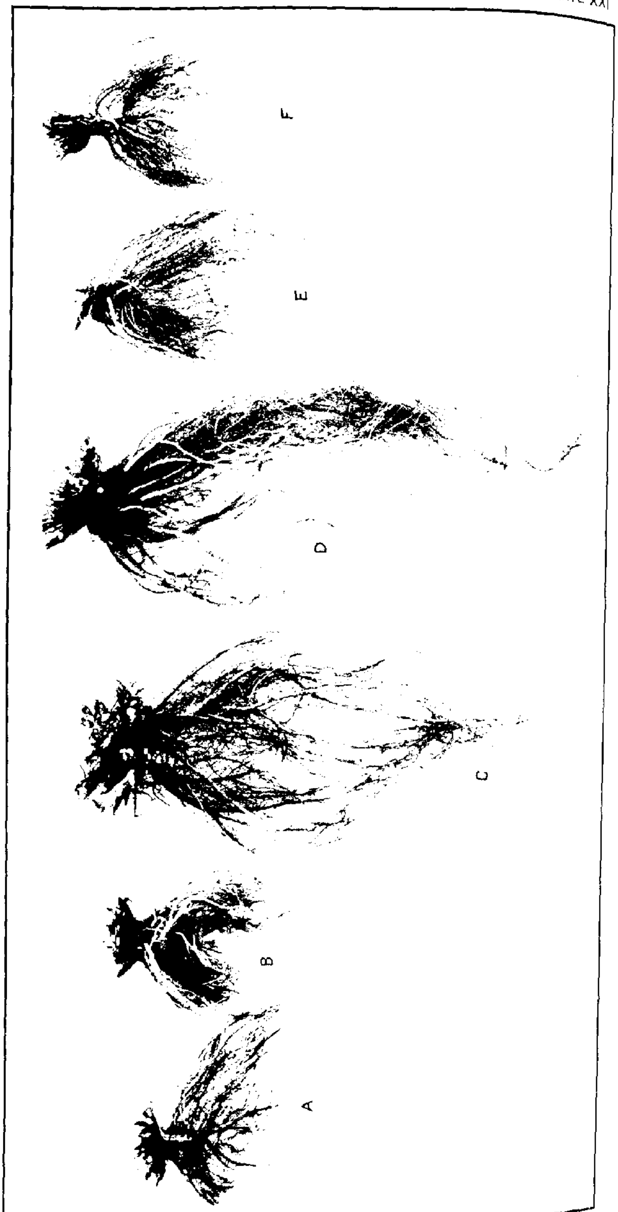

F
E
D
C
B
A

PLATE XXI

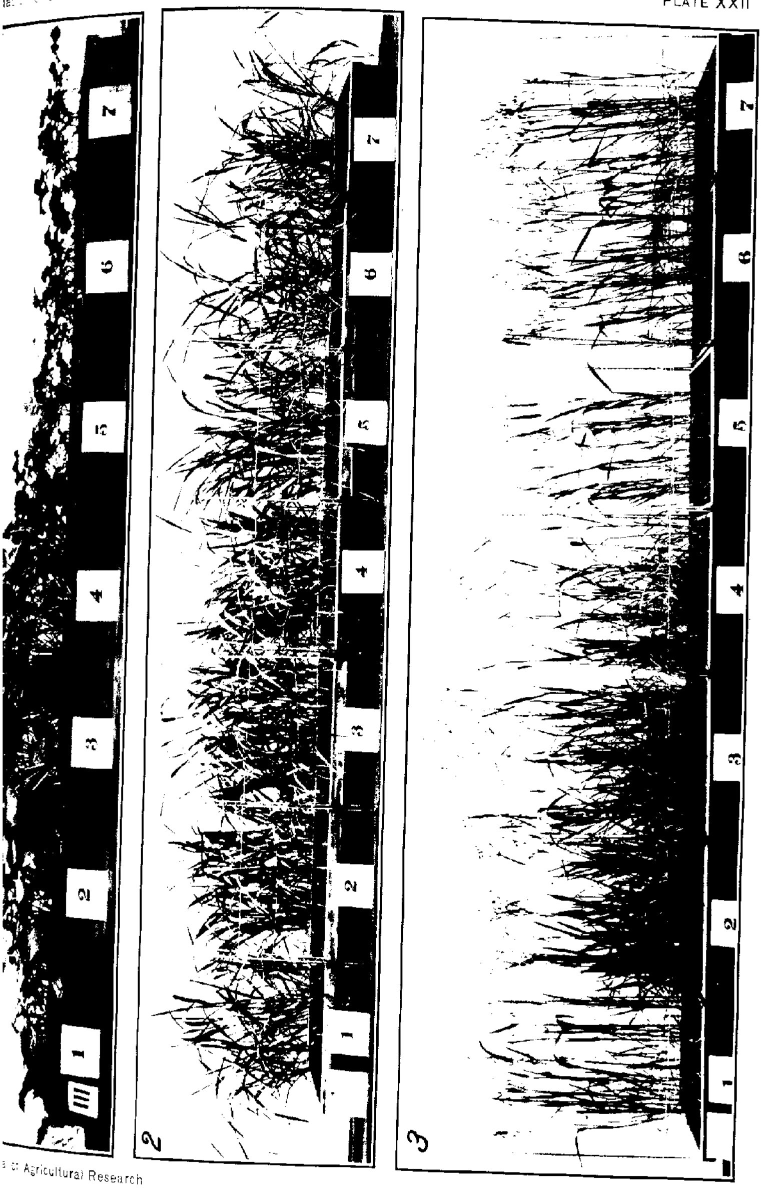
Red clover, showing effect of sulphates on growth of roots. *A*, Check; *B*, nitrogen, phosphorus, potassium; *C*, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; *D*, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; *E*, sodium sulphate only; *F*, calcium sulphate only.

PLATE XXII

Fig. 1.—Rape plants, showing influence of sulphates on growth. 1, Check; 2, nitrogen, phosphorus, potassium; 3, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; 4, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; 5, sodium sulphate only; 6, calcium sulphate only; 7, elemental sulphur only.

Fig. 2.—Barley plants, showing influence of sulphates on growth. 1, Check; 2, nitrogen, phosphorus, potassium; 3, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; 4, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; 5, sodium sulphate only; 6, calcium sulphate only; 7, elemental sulphur only.

Fig. 3.—Oat plants, showing influence of sulphates on growth. 1, Check; 2, nitrogen, phosphorus, potassium; 3, nitrogen, phosphorus, potassium, plus sulphur as sodium sulphate; 4, nitrogen, phosphorus, potassium, plus sulphur as calcium sulphate; 5, sodium sulphate only; 6, calcium sulphate only; 7, elemental sulphur only.



DISTRIBUTION OF THE VIRUS OF THE MOSAIC DISEASE IN CAPSULES, FILAMENTS, ANTHERS, AND PISTILS OF AFFECTED TOBACCO PLANTS

By H. A. Allard

Assistant Physiologist, Tobacco and Plant-Nutrition Investigations, Bureau of Plant Industry

Embryonic transmission of the mosaic disease from parent to offspring has not been observed in tobacco plants. Although the disease sometimes appears particularly malignant, so that normal capsule development is almost completely inhibited and few viable seed are produced, plants from such seed are healthy. The normal reproductive vigor of tobacco plants may not be seriously checked by the mosaic disease, especially if it makes its appearance late in the development of the plant. In such plants a nearly normal vegetative development has been attained and subsequent flowering and seed production appear to be little, if at all, inhibited.

It is of considerable interest to know how closely the embryo may be invested with tissues bearing the infectious principle of the mosaic disease. Before the question had been fully investigated the writer was under the impression that the virus ordinarily did not reach the placental column bearing the seeds. In order to test this point, three healthy Connecticut Broadleaf tobacco plants were set aside until seed production had begun. The spongy placental tissue of six to eight capsules on each plant was then punctured deeply with a needle and the virus of mosaic disease introduced abundantly. Capsules of all ages, from very young to those fully grown, were punctured and the virus injected. Although a number of the more immature capsules developed very poorly following this treatment, an abundance of seed was secured and sowed on March 31, 1914. From this seed 400 plants were obtained and later transplanted to 3-inch pots. On May 18 all were healthy, and 40 were inoculated with the virus of the mosaic disease. Practically all of those inoculated were showing symptoms of the disease on May 27 and 28.

Later experiments with affected plants have shown that the capsules of such plants normally contain the virus of the disease. The tobacco capsule contains two cells formed by a median cross wall or partition. By cutting through the thin ovary wall near this partition on both sides of the capsule the ovary wall can be readily removed in two halves, exposing to view each half of the large placental column with its attached

Journal of Agricultural Research,
Dept. of Agriculture, Washington, D. C.
ap

Vol. V, No. 6
Nov. 8, 1915
G—63

ovules. A thin, sharp scalpel heated to redness was used for cutting away the ovary wall, so that possible infection of any portion of the placental tissues from the ovary wall itself was avoided. Table I shows the occurrence of virus in the placental structure and ovules of mosaic-diseased plants.

TABLE I.—*Occurrence of virus in the placental structure and ovules of tobacco plants affected with the mosaic disease*

Date of inoculation.	Number of plants.	Variety.	Material used for inoculation.	Effect.
1914. Apr. 23	10	Connecticut Broadleaf.	Sap of portions of placental column and immature ovules of green capsules from plants affected with mosaic disease. These portions were macerated in a mortar with clean tap water.	8 affected with mosaic disease on May 9.
23	10	do	Sap of green leaves from same plants.	6 affected with mosaic disease on May 9.
23	10 (control)	do	Sap of green placentas and ovules from a healthy plant and macerated with tap water.	All healthy on May 9.
May 18	10	Maryland Mammoth	Sap of macerated placentas and immature ovules of large, green capsules of plants affected with mosaic disease.	6 affected with mosaic disease on May 26.
18	10	do	Sap of ovaries entire from the same plants.	10 affected with mosaic disease on May 26–28.
18	10	do	Thin paste obtained by grinding in a mortar with a small quantity of tap water the white and brownish immature seeds of two capsules from plants affected with mosaic disease. These seeds were scraped very carefully from the placental column.	4 affected with mosaic disease on May 28.
18	10	do	Sap of two placentas alone, from which the ovules were removed in the preceding test.	7 affected with mosaic disease on May 28.
18	10 (control)	do	Sap of immature seeds and placentas obtained from a healthy plant and ground with tap water.	All healthy on May 28.
28	10	do	Macerated placentas and immature seeds of green capsules from plant A, affected with mosaic disease.	10 affected with mosaic disease on June 6.
28	10	do	Thoroughly mature, loose seeds from dried, brown, matured capsules of the same plant, A, were poured from the capsules into a mortar and ground to a thin paste with tap water.	3 affected with mosaic disease on June 8.
28	10 (control)	do	Macerated placentas and immature seeds of green capsules from a healthy plant, mixed and ground in a mortar with dried mature seeds from the same plant. A small quantity of tap water was added to obtain a thin paste.	All healthy on June 8.
June 2	10	do	Macerated white immature ovules carefully removed from the spongy, succulent placentas of green capsules of plants affected with mosaic disease and mixed with tap water to form a thin paste.	4 affected with mosaic disease on June 10.
2	10	do	Sap of leaves from the same plants affected with mosaic disease used in the preceding test.	10 affected with mosaic disease on June 10.

TABLE I.—*Occurrence of virus in the placental structure and ovules of tobacco plants affected with the mosaic disease*—Continued

Date of inoculation.	Number of plants.	Variety.	Material used for inoculation.	Effect.
1914. June 2	10	Maryland Mammoth	Thin paste obtained by grinding with tap water in a mortar thoroughly dry, loose, ripened seeds from matured capsules of plants affected with mosaic disease.	4 affected with mosaic disease on June 10.
2	10	do	Same macerated material used as in preceding test.	2 affected with mosaic disease on June 10.
2	10 (control)	do	Paste obtained by grinding together white immature ovules from green capsules and dry, loose, ripe seeds from healthy plants. Small quantity of tap water added to thin the paste.	All healthy on June 10.
June 4	10	do	Thin paste obtained by grinding with tap water loose, dry, thoroughly ripened seeds of capsules from plants affected with mosaic disease.	7 affected with mosaic disease on June 10.
4	10	do	Sap of green leaves from the plants in the preceding test.	10 affected with mosaic disease on June 10.
4	10	do	Paste obtained by grinding and thinning with tap water dry, loose, ripe seeds from capsules of plant B affected with mosaic disease.	1 affected with mosaic disease on June 10.
4	10	do	Thin paste obtained by grinding with tap water the nearly mature, light brown seeds from ripening capsules of the same plant B affected with mosaic disease. In this test the capsules selected were still green and the placental column succulent and full. The seeds, which were firm and brownish in color, still adhered to the surface of the placenta.	3 affected with mosaic disease on June 10.
4	10 (control)	do	Paste obtained by macerating in a mortar with tap water dry, loose seeds, nearly matured seeds, and leaves of healthy plants.	All healthy on June 10.
5	10	do	Paste obtained by macerating with tap water the loose, dry seeds from ripening capsules of plants affected with mosaic disease. These seeds were mature, but the placental column was still succulent, although beginning to dry and shrink somewhat.	2 affected with mosaic disease on June 11.
5	10	do	Macerated placentas from which the seed in the preceding test was removed. Small quantity of tap water added to obtain a thin paste.	8 affected with mosaic disease on June 11 and 12.
5	10 (control)	do	Paste obtained by macerating with tap water in a mortar the dry, loose seeds and placentas of capsules obtained from healthy plants.	All healthy on June 11 and 12.

Earlier experiments[1] have shown that the roots, the apparently healthy lower leaves, and the corollas of plants affected with the mosaic disease sooner or later carry the virus of the disease. More recently experiments have been carried out to determine whether the virus is present

[1] Allard, H. A. Mosaic disease of tobacco. U. S. Dept. Agr. Bul. 40, p. 18–19. 1914.

in the filaments, anthers, and pistils of blossoms produced by affected plants. See Table II.

TABLE II.—*Occurrence of virus in the filaments, anthers, and pistils of blossoms produced by tobacco plants affected with the mosaic disease*

Date of inoculation.	Number of plants.	Variety.	Material used for inoculation.	Effect.
1914. May 21	10	Maryland Mammoth	Sap of macerated pistils extracted very carefully with forceps from the blossoms of a tobacco plant affected with mosaic disease. A gentle pull with the forceps readily severs the style at its junction with the apex of the ovary.	10 affected with mosaic disease on May 28.
21	10	do	Sap of leaves of the same plant, A.	Do.
21	10 (control)	do	Sap of the leaves and pistils of a healthy plant.	All healthy on May 28.

Experiments with the pistils of plants affected with the mosaic disease were again repeated, using only the upper portion of the style and the stigma. This was done to avoid the possibility of infection from tissues of the ovary adhering to the base of the style when extracted. See Table III.

TABLE III.—*Occurrence of virus in the upper portions of the filaments, anthers, and pistils of blossoms produced by tobacco plants affected with the mosaic disease*

Date of inoculation.	Number of plants.	Variety.	Material used for inoculation.	Effect.
1914 May 27	10	Maryland Mammoth	Macerated upper portions of pistils from plants affected with mosaic disease.	8 affected with mosaic disease on June 6.
27	10	do	Sap of leaves of the same plants.	10 affected with mosaic disease on June 6.
27	10 (control)	do	Sap of leaves and upper portions of the pistils of healthy plants.	All healthy on June 6.
June 2	10	do	Sap of anthers of plants affected with mosaic disease. These anthers were carefully removed with forceps just prior to opening, and were macerated in a mortar with a small quantity of clean tap water sufficient to make a thin paste.	10 affected with mosaic disease on June 10.
2	10 (control)	do	Sap of anthers of healthy plants extracted in the same manner.	All healthy on June 10.

From the preceding experimental data it is evident that the virus of the mosaic disease in affected plants becomes distributed throughout the placental structures, reaching even the ovules themselves. Whether the virus passes beyond the integuments of the ovules to the embryo sac has not been determined. There is some indication that the macerated placenta in a succulent condition is more effective than the immature

ovules, and especially the loose, dry, normally ripened seeds, in producing the mosaic disease in inoculated plants. Although the greatest care may be exercised in removing immature seeds from a succulent placental column, it must be evident that the probability of rupturing and removing some of the placental substance is very great. In the normal ripening process, however, the seeds loosen and fall away from the drying and shrinking placental column so gradually that the minimum amount of placental material is carried away attached to the seeds.

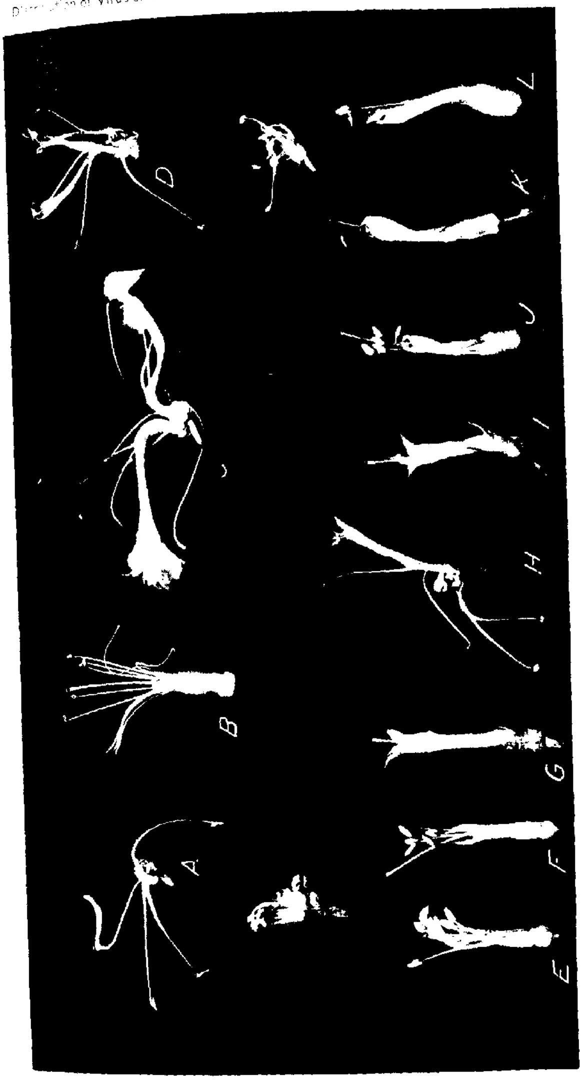
Malformations caused by the mosaic disease may disturb the normal relations of stamens and pistils to such an extent as to cause sterility in many blossoms, owing to the failure of natural self-pollination. Hand pollination of these pistils has frequently led to normal seed development. Not infrequently the development of the corolla is almost entirely inhibited and the stamens and pistils also fail to develop normally. Even in these blossoms the anthers may contain more or less functioning pollen, which has produced normal fertilization when transferred to the pistils of healthy blossoms. In some instances the anthers produce little or no functioning pollen. In extreme cases the normal form and structure of the anther sacs is replaced by a mass of irregular proliferations. Generally blossoms affected with the mosaic disease appear to produce viable pollen and ovules quite as freely as those borne by healthy plants (Pl. XXIII).

From the fact that the mosaic disease is not known to occur as the result of embryonic transmission of the disease directly from the mother plant during seed development, it is evident that a very efficient barrier guards against embryonic infection or the subsequent successful continuation of the disease from parent to seedling. In particularly malignant cases of the disease, where few or no viable seed are produced, following pollination with pollen from healthy blossoms, it is possible that the infective agents of the disease have produced embryonic infection which resulted in death. Whether the failure to produce viable seed in these instances is due to actual infection of the ovules or to a general impairment of nutrition and cell division of the capsular structures associated with embryonic development, can not at present be determined. It is possible that embryonic development never proceeds in those ovules actually invaded and infected by the virus of the disease. In all experimental tests at least germinable seeds from plants affected with the disease have always produced normal, healthy offspring.

At this time speculation seems quite fruitless, and one can only wonder what protects the embryo so securely from the mosaic disease, even though intimately associated with and nourished by infective parental tissues.

PLATE XXIII

Malformed blossoms of tobacco (*Nicotiana tabacum*) caused by the mosaic disease, which is often responsible for the various abnormalities shown. The corolla may show mottling only, or it may develop very imperfectly, producing various degrees of catacorolla, fasciation, etc. In some instances the corolla fails to develop entirely. The plants producing these acquired abnormalities as a result of the mosaic disease have been studied as to their inheritance, but the descendants were healthy and their blossoms normal. A common cause of sterility is the failure of successful pollination of the stigma, owing to the abnormal displacement of pistil and stamens. Hand pollination of such blossoms has often given capsules containing an abundance of fertile seed. Blossoms as poorly developed as A, D, and H are usually incapable of producing seed. The anthers, however, sometimes contain functioning pollen which may produce fertilization of the ovules when transferred to the pistils of healthy blossoms. Blossoms E, F, G, I, J, K, and L usually produce seed if hand pollination is practiced.


A
B
C
D
E
F
G
H
I
J
K
L

DISSEMINATION OF BACTERIAL WILT OF CUCURBITS

[PRELIMINARY NOTE]

By FREDERICK V. RAND,

Assistant Pathologist, Laboratory of Plant Pathology, Bureau of Plant Industry

In the discussion of his exhaustive studies upon bacterial wilt of cucurbits, Dr. Erwin F. Smith [1] makes the following statements relative to certain still unsolved portions of the wilt problem:

> Leaf-eating insects, and especially *Diabrotica vittata* (fig. 55), are, I believe, the chief agents in the spread of this disease. They feed readily, and sometimes the writer has thought preferably (fig. 7), on wilted leaves which are swarming with this organism. In this way their mouth-parts can not fail to become contaminated and to serve as carriers of the sticky infection. No other means of dissemination is known to the writer, and this is believed to be the common way in which the disease is distributed. * * *
>
> Seasonally the disease does not manifest itself until the leaf-eating beetles have put in their appearance, and this has led to the suspicion that the organism might pass the winter inside the bodies of these hibernating insects (*Diabrotica vittata*). As to this nothing definite is known.

He has referred to this subject again in his St. Louis address,[2] as follows:

> The writer has since proved several diseases to be transmitted by insects, notably the wilt of cucurbits, and here the transmission is not purely accidental, but there appears to be an adaptation, the striped cucumber beetle (*Diabrotica vittata*), chiefly responsible for the spread of the disease, being fonder of the diseased parts of the plant than of the healthy parts. This acquired taste, for it must be that, works great harm to melons, squashes, and cucumbers. Whether the organism winters over in the beetles, as I suspect, remains to be determined. Certainly the disease appears in bitten places on the leaves very soon after the spring advent of the beetles.

It was especially with a view toward throwing some light on the mode of hibernation of the causal bacteria and of developing some practical method of control that the writer undertook to continue the studies upon this frequently very destructive disease. Since the study was begun in midsummer (July, 1914), the first season's work consisted largely of field observations which covered the territory from eastern Long Island, N. Y., and Maryland to Indiana and Wisconsin. Some of the worst examples of injury from wilt were found in eastern Long Island, and accordingly this locality was selected for the field tests of the following season (1915). While further investigations are under way, it appears

[1] Smith, Erwin F. Bacteria in Relation to Plant Diseases. v. 2, p. 215. Washington, D. C., 1911.

[2] ——. A conspectus of bacterial diseases of plants. *In* Ann. Mo. Bot. Gard., v. 2, no. 1/2, p. 390, 1915.

Journal of Agricultural Research,
Dept. of Agriculture, Washington, D. C.
aw

Vol. V, No. 6
Nov. 8, 1915
G—64

desirable to record at this time the result of the first season's experimentation.

At East Marion, Long Island, N. Y., two fields were selected where during the season of 1914 about 75 per cent of the cucumber vines (*Cucumis sativus*) had been destroyed by bacterial wilt, as determined by the writer. Here was an excellent environment in which to test the question as to hibernation of the bacteria in soil *v.* animal carriers. Fifty large frame cages 4 feet square and 3½ feet high were constructed. The lower 18 inches of the sides were boarded up, while the covers and the upper 2 feet were inclosed in 18-mesh wire mosquito netting. These bottomless cages were set 15 inches into the soil, leaving 3 inches of the boarded portion above the soil line. The juncture between cover and sides was sealed with cotton and liquid tar, and the cracks between the boards of the basal portion were stuffed with cotton to prevent access of insects. Twenty-three of these cages were set in one of the fields and twenty-seven in the other. In each field the soil in four cages was sterilized by live steam at 75 pounds' pressure for one hour, but this made no difference in the final result. This was done in order to kill any wilt bacteria which might have wintered over in the soil. In each field the cages containing sterilized and unsterilized soil were located at intervals across the field and cucumbers were planted in the usual way in the soil between and within the cages on June 5 and 6. A half-dozen plants were grown in each cage and later on thinned to three or four. After planting, the cages were all sealed with lead seals to preclude accidental opening of the covers, and whenever necessary to open the cages for examination they were again sealed in the same manner. By this careful construction and setting of the cages it was thought possible to exclude all of the insects injurious to cucumbers except possibly aphides and flea beetles, some of both of which later on entered some of the cages through the wire netting, but were without effect upon the experiment.

Field No. 1 was separated by at least one-half mile, including a quarter-mile depth of woods, from the nearest cultivated cucurbits. It was, in fact, surrounded on three sides by woods and on the fourth side by Long Island Sound.

Field No. 2 was about one-quarter mile from other cucurbits, but without the intervening woodland.

Plate XXIV, figure 1, shows the cages in place in field No. 2; Plate XXIV, figure 2, shows field No. 1, with a cage in the foreground lifted, the darker part of the base indicating the depth buried.

No commercial cucumber fields were planted in either locality until two or more weeks later in the season.

As soon as the young plants were 2 or 3 inches high and before any wilt had appeared, five or six striped cucumber beetles were introduced into each of 4 cages, 2 in each experimental field. These beetles were

collected in field No. 1, where presumably they had hibernated. Within a week several plants in 1 of the 2 cages in field No. 1 into which the beetles had been introduced showed signs of wilt, starting from points in the leaves gnawed by the beetles. Upon cutting off the stems the typical stringing out of the viscid white bacterial slime was seen. Cultures were made by the writer from one of these plants and subsequent inoculations from these cultures into healthy plants again gave the disease. Other wilted plants from the same cage were sent to Washington, D. C., and from one of these *Bacillus tracheiphilus* was obtained and with it successful inoculations were made in cucumbers in one of the Department greenhouses by Dr. Smith. No signs of wilt occurred in the 3 other cages in which beetles were placed, or, with one exception, in any of the 46 other cages.

Meanwhile in both fields the wilt was beginning on plants between the cages. At first the wilt appeared only on a plant here and there, and then gradually extended throughout the two fields until no portion was entirely exempt. In the two fields together there were in the neighborhood of 1,200 hills of cucumbers exposed to attack of the beetles. The cages in field No. 1 extended approximately a quarter of a mile through the field at equal distances and in field No. 2, which was about two-thirds as large, they were spaced closer. There was a check plot contiguous to each cage. The approximate number of cases on the plants in field No. 1 during the three months was 600; in field No. 2 it was 200. No counts were made after September 1, owing to the appearance of the cucumber mildew (*Plasmopora cubensis*).

In all these cases of wilt in the exposed (uncovered) plants, infection was clearly seen to have started from beetle injury. Careful record was kept throughout the season of every hill and plant showing wilt, and although between the cages the disease was everywhere present the plants within the cages were strikingly free from the disease. The plants in these 50 cages were examined every day from planting time (June 5–6) until September 1. In one cage where beetles were not liberated, wilt was noted just starting in the tip leaf of one plant at a point gnawed by a beetle. A careful search in this cage disclosed a striped beetle, which was summarily disposed of. Microscopical examination and cultures from the lower part of the stem failed to disclose any bacteria, showing that the wilt in this case could not have come from the soil and must have been brought in by the beetle, which probably entered through a crack due to warping of the boards. Careful search failed to disclose any further beetle injury within the cage, and, after the removal of the beetle and the one wilting plant, no further signs of the disease appeared therein during the season. With this exception and that of the above-mentioned 1 cage into which the beetles were purposely introduced, not a case of wilt occurred in any of the 50 cages during the entire season.

From these cage experiments therefore it would appear that the wilt bacteria are carried over the winter by the hibernating beetles and inoculated into the cucumbers as they feed upon the young leaves. However, from the fact that wilt appeared in only one of the four cages into which beetles were introduced, it would seem that not all hibernating beetles carry the disease, but only those, or some of those, which have previously fed upon wilted plants. In other words, the beetles act not only as summer but also as winter carriers of the wilt organism from one cucumber plant to another. At least the above facts seem to warrant this as a tentative conclusion. The only possible alternative is to suppose that some of the beetles captured on June 17 and introduced into the four cages had recently had opportunity to gnaw diseased plants, which under the circumstances of their capture appears to the writer out of the question. Finally, in addition to the positive evidence of insect transmission afforded by this cage and by the one into which a beetle accidentally penetrated, as well as by daily observation on the check plants, there is the negative evidence afforded by the fact that in all cages from which beetles were excluded the plants remained free from the disease in two fields where it was very prevalent.

PLATE XXIV

field No. 2, with beetle-proof cages in place.
Fig. 2.—Field No. 1, with one of the cages lifted to show structure of the buried part.